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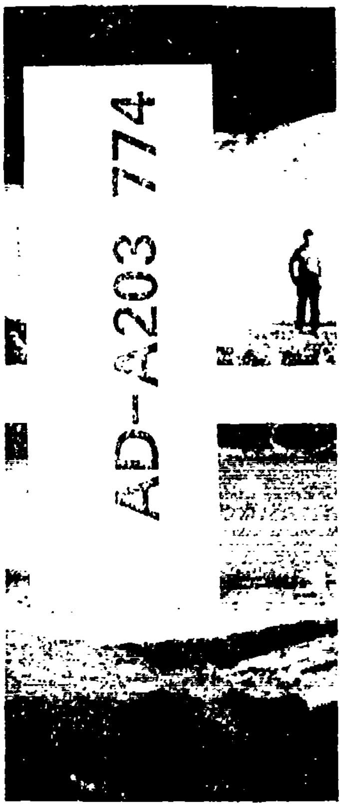

REMR RESEARCH PROGRAM

REPAIR, EVALUATION, MAINTENANCE, AND REHABILITATION RESEARCH PROGRAM

TECHNICAL REPORT REMR-GT-3

GEOTECHNICAL ASPECTS OF ROCK EROSION IN EMERGENCY SPILLWAY CHANNELS

Report 2
ANALYSIS OF FIELD AND LABORATORY DATA

by

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CS	Concrete and Steel Structures	EM	Electrical and Mechanical
GT	Geotechnical	EI	Environmental Impacts
HY	Hydraulics	OM	Operations Management
CO	Coastal		

COVER PHOTOS

TOP -- Rock protection structure in emergency spillway channel at Black Butte Reservoir (California)

MIDDLE -- Spillway discharge shortly before weir failure at DMAD Reservoir (Utah).

BOTTOM -- Results of erosion in emergency spillway channel at Saylorville Reservoir (Iowa).

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Field and laboratory studies of erosion in unlined emergency spillways channels excavated in rock have demonstrated that erosional processes operating in these spillway channels are similar to those operating in natural stream channels and that rock discontinuities are critical factors in the initiation and extent of erosion. Knickpoint formation and headcutting are typical erosion processes. Fractures, faults, joints, dip orientation, igneous contacts, veins, bedding planes, unconformities, bed pinch outs, and facies changes are types of structural or stratigraphic discontinuities which must be characterized if present. The analysis of 14 Soil Conservation Service and 2 Corps of Engineers dams which have experienced emergency spillway flow revealed that the extent of erosion at these sites could be categorized in terms of volumetric and horizontal erosion rankings. These ranking parameters provide insight as to the seriousness of the erosion threat at a particular dam

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19. ABSTRACT (Continued).

and may be used to give priority for remediation. Generally, the ranking parameters were more closely correlatable with the geometry of the spillway channel than with the hydraulics of the spillway flow event. Preliminary laboratory studies using a recirculating, tilting flume and simulated earth materials configured as a knickpoint (waterfall) demonstrated that maximum undermining and erosion of a stratified, two-layer system was a function of the ratio of water depth to knickpoint height and the venting condition of the waterfall. The maximum erosion did not occur at peak discharge but occurred when the discharge passed through windows or thresholds on the rising and falling limbs of the hydrograph which were, in turn, controlled by the ratio (above) and venting. These field and laboratory investigations have substantiated the need for detailed geological information at sites experiencing spillway flow, detailed documentation of the results of spillway flow, and model studies in which spillway geometries are evaluated in terms of geology and nature and spacing of discontinuities.

PREFACE

This study addresses rock erosion in emergency spillway channels, a problem area of the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program being conducted by the US Army Engineer Waterways Experiment Station (WES).

This second report of a series summarizes work performed during FY 87. Results of work currently in progress and ongoing research programs will be topics of further reports to be completed during FY 88 and FY 89. This study was under the direct supervision of Messrs. J. S. Huie, the Problem Area Leader, and J. H. May, the Principal Investigator, Engineering Geology and Rock Mechanics Division (EGRMD), Geotechnical Laboratory (GL). General supervision was provided by Dr. Lawson M. Smith, Chief, Engineering Geology Applications Group (EGAG), EGRMD; Dr. D. C. Banks, Chief, EGRMD; and Dr. W. F. Marcuson III, Chief, GL.

Mr. James E. Crews and Dr. Tony C. Liu served on the overview committee and Mr. Ben Kelly was REMR Technical Monitor at Headquarters, US Army Corps of Engineers. The REMR Program Manager was Mr. William F. McCleese, Concrete Technology Division, Structures Laboratory, WES.

This report was written by Drs. Christopher P. Cameron and David M. Patrick, Department of Geology, University of Southern Mississippi; Mr. Kerry D. Cato, Department of Geology, Center for Engineering Geosciences, Texas A&M University; and Mr. James H. May, EGRMD. Mrs. Joyce H. Walker, Information Products Division, Information Technology Laboratory, edited the report.

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COL Dwayne G. Lee, EN, was the Commander and Director of WES. Dr. Robert W. Whalin was the Technical Director.

CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
acres	4,046.873	square metres
acre-feet	1,233.489	cubic metres
cubic feet	0.02831685	cubic metres
cubic yards	0.7645549	cubic metres
degrees (angle)	0.01745329	radians
feet	0.3048	metres
inches	2.54	centimetres
miles (US statute)	1.609347	kilometres
square feet	0.09290304	square metres

GEOTECHNICAL ASPECTS OF ROCK EROSION IN EMERGENCY SPILLWAY CHANNELS

ANALYSIS OF FIELD AND LABORATORY DATA

PART I: INTRODUCTION

Background

1. Prediction of initiation, rate, and intensity of erosion in earth materials is not a precise science, and a significant amount of erosion-induced damage has occurred in unlined emergency spillway channels at flood-control and water-storage projects built and managed by the US Army Corps of Engineers (CE), other Federal agencies, state, and local interests. The potential for severe erosion of the bedrock (and associated soils) in unlined emergency spillways to cause undermining or failure of spillway structures and catastrophic release of reservoir waters, damage to dam embankments, spillway channel bank failure, and sedimentation in the spillway exit and main channel prompted the CE to include this problem as a work unit in the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program being conducted by the US Army Engineer Waterways Experiment Station (WES).

Objectives

2. The objectives of this work unit include the following:

a. To identify and document the geotechnical and hydraulic parameters influencing the rate and mechanisms of erosion in unlined emergency spillway channels.

b. To identify and document channel response to emergency spillway flow and to assess the nature, magnitude, and severity of downstream impacts.

c. To develop methods of predicting erosion in unlined emergency spillway channels.

d. To develop cost-effective remedial and preventive measures to minimize the problem of severe erosion in unlined emergency spillway channels.

e. To maintain and continually up-date an observational data base which documents important erosive spillway overflow events at CE projects.

f. To provide timely technology transfer in this problem area to CE personnel and other interested parties in Federal, state, and local agencies.

Scope

3. This report, the second in a series, provides further documentation of the causes-and-effects of bedrock erosion in emergency spillway channels, the relationship between spillway channel erosion and erosion in natural stream channels, provides detailed analyses, and attempts to quantify the phenomena and processes identified and discussed in the first report (see Cameron et al. 1986). These phenomena and processes encompass the geotechnical and hydraulic factors which control spillway channel response to overflow events.

4. These reports are intended to serve as a mechanism for communicating research results, ideas, and concepts to interested CE personnel and their counterparts in other Federal, state, and local agencies. CE District experience, case histories, and site visits, as well as technical input from other concerned agencies, continue to provide vital elements of the working observational data base and serve as the foundation for development and refining of research tasks.

PART II: KNICKPOINTS AND HEADCUTTING--THEIR OCCURRENCE, ORIGIN, AND SIGNIFICANCE IN FLUVIAL SYSTEMS

Background

5. The interrelated effect of stratigraphic and structural discontinuities and channel gradient change is a major erosion controlling factor in spillway discharge channels underlain by sedimentary, volcanic, metamorphic, or other stratified rock, and by structurally deformed rocks. Stratigraphic and structural variability in particular can control the position of channel knickpoints, where resistant layers are undercut by scouring of softer, underlying strata.

6. Full understanding of the phenomena of knickpoint generation is essential to adequately assess the probability of severe or excessive scour in those spillway channels underlain by stratified rock sequences. From the standpoint of facility safety, headward migration of a knickpoint (headcutting) in a spillway channel is probably the most dangerous of channel responses to sudden flow. Also, the interruption of the channel equilibrium profile resulting from the formation of a knickpoint usually results in channel degradation and incision downstream from the knickpoint. In turn, increased downcutting may cause the discharge channel banks to become oversteepened, thereby increasing the probability for mass wasting of bank material into the channel.

7. The Saylorville (Iowa) spillway case history, which is documented fully (Cameron et al. 1986), provides a good example of the scenario described above. Channel-bank oversteepening and failure by slumping occurred immediately downstream from the pronounced "stairstep" waterfall formed during the passage of floodwaters during the period June to July 1984.

Structural and Stratigraphic Discontinuities

8. The influence of structural and stratigraphic discontinuities on erosion processes affecting unlined spillway channels is noted in EM 1110-1-1603 (31 March 1965) and also discussed in Cameron et al. (1986). The latter authors emphasize the concept that discontinuities in earth materials often control the location and geometry of channel gradient changes (knickpoints),

which can occur as abrupt waterfalls, as a series of closely spaced stair-steps, or as gentle, subtle changes in channel slope. Such changes are often influenced by large-scale stratigraphic and structural discontinuities such as stratigraphic pinchouts (e.g., sandstones wedging out abruptly against shales), faults, fractures, jointing of bedrock, igneous contacts, and dissolution cavities (such as those common to carbonate and evaporite rocks).

9. Detailed engineering geological maps and cross sections parallel and normal to the channel axis which provide maximum understanding of the nature and distribution of discontinuities in the rocks underlying emergency spillway channels are essential to meaningful evaluation of erosion potential (particularly headcutting) at site-specific levels.

Definitions and classifications

10. Murphy (1985) defines "discontinuity" as all perceivable breaks or divisions in a rock mass. Strictly speaking, this definition embraces any interruption in lithologic and physical properties (e.g., mineralogy, rock fabric, structure, etc.) and would, therefore, encompass features observable only on microscopic scales such as microfractures. However, as pointed out in Cameron et al. (1986), severe channel response to emergency spillway flow, particularly in CE spillway channels, appears to be governed more by discontinuities which occur on a megascopic scale rather than on a microscopic or grain-to-grain basis. To maintain consistency in usage, definitions of specific types of discontinuities discussed in the following sections are those given in Glossary to Geology (American Geological Institute 1980).

11. It is possible to classify discontinuities under two broad headings--structural and stratigraphic. Structural discontinuities can occur in all rock associations; whereas, stratigraphic discontinuities are usually limited to stratified rock sequences (sedimentary rocks and their metamorphic equivalents) including those hosting or admixed with volcanic igneous rocks, (lavas, tuffs, volcanic breccias, and volcano-clastic sedimentary rocks).

12. Dissolution pits, cracks, and cavities result from chemical weathering and erosion and comprise a special type of discontinuity. Although most common in carbonate (limestones and dolomites) and evaporite (gypsum, anhydrite, salt, etc.), dissolution features can also occur occasionally in other rock associations as well.

Structural discontinuities

13. Structural discontinuities are caused by movements resulting from

natural compressive and tensional stress fields which affect rock masses in the upper crust of the earth. The resulting rock deformation produces folds, fractures, faults, joints, and, in the case of some orogenic belts, regional metamorphism and the forceful injection of molten rock and other fluids. Depending on the rock associations involved at a given crustal level, these processes can result in variable orientations of such planar structural elements as stratal dip, schisosity, foliation, formation of igneous contact zones, and veins, all of which have significance as important structural discontinuities from an engineering point of view. Detailed discussion of the numerous, complex, and often contentious hypotheses dealing with the origin of many structural discontinuities is beyond the scope of this report. Only those aspects or features which impact or control erosional processes in spillway channels are discussed here.

14. Fractures. The term "fracture" in structural geology is used to denote any break in a rock mass due to mechanical failure by stress, whether or not displacement of adjacent rock occurs along the surface or zone of failure. Generally, the term encompasses all cracks, joints, or faults. Although most fractures in rocks are naturally occurring, they can also be induced during excavation activities in some "hardrock" spillways. Figure 1, for

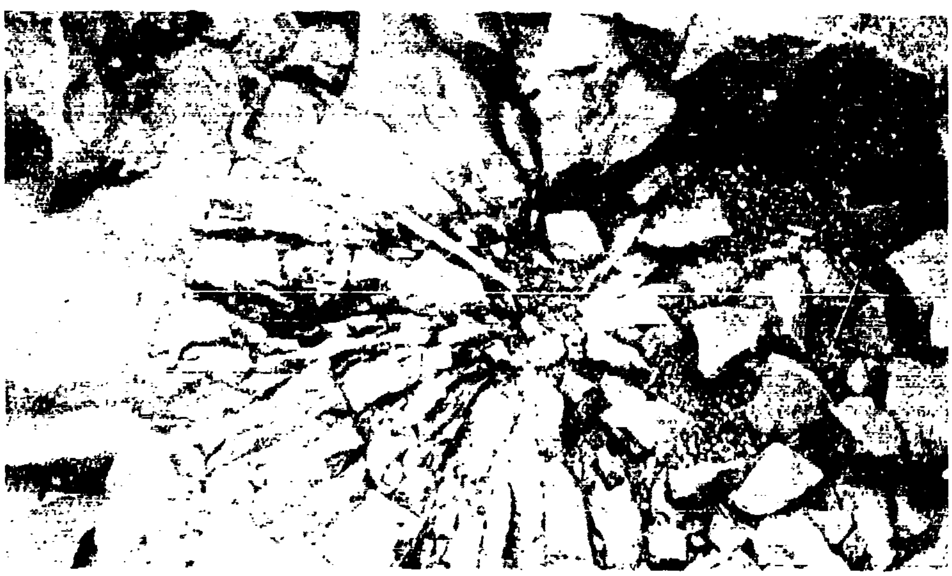

Figure 1. Blasting during excavation of a cut spillway results in a distinctive fracture pattern in hard igneous rock forming the floor of the emergency spillway channel in Lower North River Site 81C (Virginia)

example, illustrates the fracture pattern typically caused by blasting during the construction phase in an excavated emergency spillway channel.

15. Faults. Faults are surfaces or zones of rock fracture along which there has been displacement, from a few centimeters to a few kilometers in scale. Recognition of faulting in the bedrock underlying an emergency spillway channel is of prime importance to the evaluation of its susceptibility to erosion. Displacement of rock masses indicates that rocks of differing erodibility can be juxtaposed. When such juxtaposition occurs in a natural or cut emergency spillway channel, differential erosion across the fault can result in the formation of a knickpoint.

16. Because faulting can involve significant displacements of adjacent rock masses, it is not uncommon that the rocks on either side of a fault plane or zone are significantly disrupted. Shearing, brecciation, and drag-folding are all common features of fault zones. Whereas rock breakage and crushing are involved in shearing and brecciation, rapid change in dip orientation is most common in drag-folding. Such structural alteration of original rock masses may also result in localized chemical alteration and disaggregation of affected rock, phenomena which generally render fault zones particularly susceptible to erosion, as evidenced by the pronounced control exerted on natural streams by such zones.

17. Approximate fault orientation(s) and displacement(s) are usually defined by geological studies conducted on regional scales, and usually rigorous attempts are made to avoid siting major engineered works on foundations which have been directly affected by faulting. Detailed geological mapping similar to that conducted in core trenches, including drilling to accurately define fault orientation(s) and displacement(s), are always essential in those cases involving the inadvertent or deliberate siting of dams, spillway structures, or emergency spillway channels on bedrock which has been affected by faulting.

18. Joints. Joints are planar surfaces of actual or potential fracture or parting in a rock mass, along which no displacement has occurred. These planar surfaces never occur alone. They usually occur in parallel sets. Joint sets of differing orientations often combine to form joint systems of variable dimensions depending on the nature of the rock and the forces which produce the fractures. For example, sedimentary rock strata often exhibit joint sets parallel to the dip and strike of the beds. These sets can be

complimented by intersecting joint sets which are oblique to the strike direction and most often occur in high angle conjugate pairs. Igneous rocks can exhibit a variety of joint types. Cooling of an igneous rock mass generally involves the creation of tensional joints, the most extreme case typified by the polygonal (columnar), joints of some basaltic lavas. During the intrusive stage of some igneous rock masses, compressive and shear forces may dominate and produce additional joint sets.

19. Joint spacing (i.e. the perpendicular distance between joints of a given set) can be highly variable, with intervals in the range of hundreds of feet down to only a few feet. Where the joint separation is only a fraction of an inch, the term "fracture cleavage" is most appropriate. Joint fissures are the actual fractures which separate the rock. Joint fissures may be tight and filled with mineral-bearing material (clays, crushed rock fragments, sand-like gouge, calcite, gypsum, etc.), particularly in the subsurface, but are often open in the surface and shallow subsurface weathering regimes (Figure 2). The size of the fissure opening (aperture size), or joint-block separation, is often a function of proximity to the surface and slope of the ground or free-air surface. For example, field investigations at the Saylorville, Iowa, emergency spillway showed that the joint fissures in the hard competent sandstone bed forming the floor of the upstream portion of the channel exhibited progressive opening as the downstream terminus of the bed is approached (Figure 3). A similar situation is present at the Black Butte, California, spillway where the fissures in jointed basalt have been opened at the downstream falls by both erosion of fissure fillings and downslope movement of the blocks during flow events (Figure 4).

20. Joints can be considered as fractures which serve to divide rock masses into blocks. If the blocks are relatively small (on the order of inches and feet), and if the fissures separating them are open, then the blocks are susceptible to movement or even complete removal (by uplift and plucking) during emergency spillway flows (Figure 4). Hence, joint surface orientation, joint set spacing, joint continuity, and joint fissure separation, are all key parameters with respect to evaluation of the rate and extent of rock erosion in emergency spillway channels.

21. Veins. Veins are epigenetic mineral fracture fillings in rock masses and often are tabular, sheet-like, or pod-shaped in form. In highly fractured terranes, veins can form branching systems (both in plan and cross

Figure 2. Opening in filled joints and fissures in siltstone and shale forming the floor of an (SCS) emergency spillway channel in Virginia

Figure 3. Open joint fissures segment the hard resistant sandstone which floors the upstream portion of the Saylorville spillway (US Army Engineer District, Rock Island (NCR)). Undercutting and retreat of the soft, erodible shale beneath resulted in collapse of the sandstone and the formation of a waterfall

Figure 4. Weathering and the effects of scour during flows in 1983 and 1986 removed fissure fillings of clayey weathered basalt and mudstone from joints and fractures in basalt forming the downstream terminus of the Black Butte (US Army Engineer District, Sacramento (SPD)) spillway channel

section), and chaotic "swarms." Epigenetic mineral fillings, while often confined to the fissure separation, can occasionally replace the adjacent rock mass, particularly in hydrothermal systems of mineral deposition. Although quartz and carbonates are by far the most abundant vein-filling minerals, other mineral species including clays, gypsum, and sulfides are common.

22. Because veins are often composed of mineral species which differ markedly in their resistance to erosion than do their host rock, their occurrence in spillway channels must be highlighted. This is particularly important in those situations where vein introduction has resulted in alteration of the host rocks. Whereas quartz veining usually results in a vein mineralogy which is more resistant to erosion than the surrounding rocks, sulfide mineralization may be accompanied by silicification of the adjacent host. In the latter case the vein material is often more susceptible to erosion, all other factors being equal.

23. Igneous contacts. Where molten rock has been forcefully injected or intruded into the upper crust, a contact zone between the intrusion and the host rock is invariably present. This zone is of variable dimensions--from a narrow interval of thermal alteration a few inches or feet in width to intervals extending outwardly from the intrusion for several thousand feet or more. The width of the zone of contact is a function of original depth of intrusion, prevailing temperature gradients, the composition of the intrusion and the host terrane, water gradients between the intrusive and the host terrane, and the slope of the intruding rock mass relative to overlying and intruded host rocks.

24. Igneous contact zones, especially those which span a narrow width, invariably form knickpoints in natural channel systems. Substantial differences in mechanical rock properties and erodibility between the intrusive and host terrane are common; a situation which generally leads to differing rates of erosion on either side of the zone of contact. The resulting change in channel gradient may lead to the formation of falls or rapids if the less resistant rock is downstream of the contact. On the other hand, differential erosion immediately upstream of the contact may result in the formation of a hydraulic jump if the downstream reach is underlain by the harder, more resistant lithology.

25. Orientation of dip, schistosity, and foliation. The spatial orientation of stratal dips is of prime importance in the evaluation of bedrock

erodibility in unlined emergency spillway channels. Stratal dip of a given stratified rock sequence lends structural and stratigraphic inhomogeneity to the section and results in pronounced differential erosion between beds of variable resistance. Pronounced dip and strike changes are indicative of fold axes (or faulting) and may also serve to localize erosional effects, particularly from the standpoint of diverting flow into channel banks.

Stratigraphic discontinuities

26. Stratigraphic discontinuities include depositional features such as bedding planes, bed contacts, unconformities, sedimentary structures and textures, as well as bed pinch outs and facies changes within the same lithostratigraphic unit. As previously indicated, stratigraphic discontinuities are limited to stratified sedimentary rock sequences including those interbedded with volcanic rocks and their clastic derivatives. As before, definitions included in the discussion below follow those given in Glossary of Geology (American Geological Institute 1980).

27. Bedding planes and bed contacts. Also referred to as "planes of stratification," bedding planes are surfaces of deposition that visibly separate each successive layer of stratified rock from its preceding or following layer. These planes or "breaks" in bedding separate bedding "lamina" (less than 1 cm in thickness), "stratum" (greater than 1 cm in thickness), and "beds" which are thicker units composed of several strata or lamina. Bedding planes and bed-to-bed contacts often mark changes in the circumstances or environment of deposition and may highlight pronounced partings between beds, changes in color, texture (particle size), sedimentary structures, and rock composition. From the standpoint of rock erosion, bedding planes will tend to behave mechanically in a manner similar to dip-parallel joint sets (with which they are sometimes confused). The intersection of strike-parallel and diagonal joint sets with bedding planes and partings divide sedimentary strata into blocks which can be removed by erosion. Shales are often composed of multiple layers of thin lamina and tend to break apart along bedding planes, especially in weathered surface and shallow subsurface zones.

28. Sedimentary structures and textures. Sedimentary structures (including large-scale cross stratification, load casts, slump structures, mud cracks, concretions, bioturbation, and root mottling), particularly when combined with sudden shifts in texture (intraformational conglomerates, graded bedding, zones of fossil accumulations), serve to interrupt the internal

homogeneity of beds. Because sedimentary structures and textures often influence the distribution of cementing agents in sedimentary rocks (and hence, their hardness and resistance to scour), they should be carefully described and mapped during spillway construction and subsequent evaluation. As well, variations in sedimentary structures and textures are indicators of the energies available in the original depositional environment(s) and their recognition and documentation often serve as a means to estimate bed continuity, or, more importantly, lack of the same.

29. Unconformities. Unconformities represent potentially important stratigraphic discontinuities from the standpoint of rock mass erodibility. In fact, they can be regarded in some cases as being analogous to faults in that they often juxtapose, in a vertical sense stratigraphically, rocks of vastly different compositions, hardness, mechanical behavior, and resistance to erosion. By definition, unconformities are substantial gaps in geologic record where a rock unit is overlain by another that is not next in stratigraphic succession, such as an interruption in the continuity of a depositional sequence (implying a shift in depositional environments following an interval of nondeposition or erosion) or a break between eroded igneous rocks and younger sedimentary strata. These phenomena generally result from changes which cause deposition to cease for a significant period of time or from uplift and erosion with loss of the previously formed record. An "angular unconformity," for example, involves a plane of separation (again representing a considerable span of time) between older strata which have been folded, uplifted, and truncated by erosion and younger sedimentary strata (or volcanics) which overlay the plane of unconformity horizontally or subhorizontally.

30. Because unconformities are planes of separation which may juxtapose rocks of vastly different engineering properties, structural integrity, and erodibility, their identification and documentation in the vicinity of engineered structures is of considerable importance.

31. Pinch outs and facies change. Stratigraphic pinch outs occur when a given bed thickness (or sequence of beds) narrows progressively in a given horizontal direction until the bed(s) disappears and the enclosing rocks are in direct contact with each other. The lithologic character of the thinning unit is typically maintained to the feather-edge of the layer.

32. Facies changes encompass a wide variety of lateral and vertical

variations in the lithologic or paleontologic characteristics of contemporaneous sedimentary rocks. From the standpoint of erodibility, facies changes are important because they can take place laterally within the same unit over relatively short distances, changing the mechanical and engineering properties of the rock and hence its resistance to erosion.

33. Stratigraphic pinch-outs and facies changes are of considerable importance in that, like faults and unconformities, they also often result in the juxtaposition of rocks and widely varying competence and resistance to erosion. For example, at Grapevine spillway (US Army Engineer District, Fort Worth (SWF)), the pinch out of a moderately bedded sandstone unit controlled the location of a channel gradient change (knickpoint). The steepened downstream reach, being underlain by soft, weathered, erodible shales, reacted negatively to the second spillway event, (in 1983). Rapid undercutting of the shale substrate resulted in collapse of the sandstone layer and headward retreat of the knickpoint. A large stilling basin was constructed at a cost of $10 million to inhibit further headcutting during emergency spillway overflow. Other cases are cited in Cameron et al. (1986).

34. Lithostratigraphic continuity. Lithostratigraphic continuity is a key factor controlling the rate and intensity of spillway erosion in stratified rock sequences. Rapid changes in lithostratigraphic facies, both laterally and vertically, appear to control the location and rate of headward retreat of knickpoints and waterfalls, locally maximizing hydraulic energies and scour intensity. It is, therefore, appropriate to comment briefly on the controls of lithostratigraphic continuity.

35. In the absence of folding or faulting, stratigraphic pinch outs and other facies changes are response models to changes in original depositional environment(s). A knowledge of depositional environments and the tectonic elements which control their change is a powerful tool in the analyses and prediction of lithofacies distribution and continuity in sedimentary rock sequences. For example, the deposits of widespread, shallow seas tend to be remarkably uniform in bedding morphology and composition, particularly when developed in carbonate facies. Relatively thin-to-moderately bedded limestone and dolomite deposited in these environments can often be traced for miles without significant changes in composition or character.

36. Nearshore marine, shore zone, and fluvial deposits tend to be characterized by more pronounced changes in lithofacies morphology and continuity.

Some shore zone deposits (e.g. beach sands, barrier bars and islands) have preferred depositional strike development; whereas, others (e.g. tidal channels) have maximum thickness and continuity along depositional dip. The occurrence, maximum size, and distribution of some meanderbelt point bar sandstones are relatively easy to predict with a minimum of data. On the other hand, the rapid facies changes which are characteristic of braided streams are more difficult to predict even with large amounts of surface and subsurface data. The list is extensive and beyond the scope of this report. However, modern methods of facies analysis allow for the identification of most sedimentary depositional environments. It can also be stated with some assurance that knowledge and understanding of the depositional system(s) responsible for the formation of a given stratified sequence allows for meaningful estimates of facies variability and lithostratigraphic continuity on both regional and local scales. The interested reader is referred to Sedimentary Environments and Facies (ed. H. G. Reading 1986) for a thorough and very readable account of methods and concepts in facies analysis and interpretation.

Description and quantification of discontinuities

37. If structural and stratigraphic discontinuities are to be used effectively in the evaluation and prediction of bedrock erodibility in unlined emergency spillway channels, rigorous attempts must be made to accurately describe and quantify the features discussed above. Comprehensive schemes for describing and quantifying the above features are given by Murphy (1985). The potential use of structural and stratigraphic discontinuities in deriving semiquantitative erosion probability indices is described in Report 3 of this series (Cameron et al., in preparation).

Knickpoints in Natural Stream Channels

38. Generally, the term "knickpoint" refers to a point along the longitudinal profile of a stream channel at which there is an abrupt change in gradient (American Geological Institute 1980). The change in gradient may be large in which case visible rapids or waterfalls will characterize the point at which the change occurs (Figure 5). If the change in gradient is small, the point at which the change occurs may only be evident from topographic data or from measurements of the channel bottom (Figure 6). The position of the

a. Hotopha Creek

b. Tillatoba Creek

Figure 5. Photographs showing natural stream channel knickpoints, Yazoo Basin Uplands, Mississippi (after Whitten and Patrick 1981)

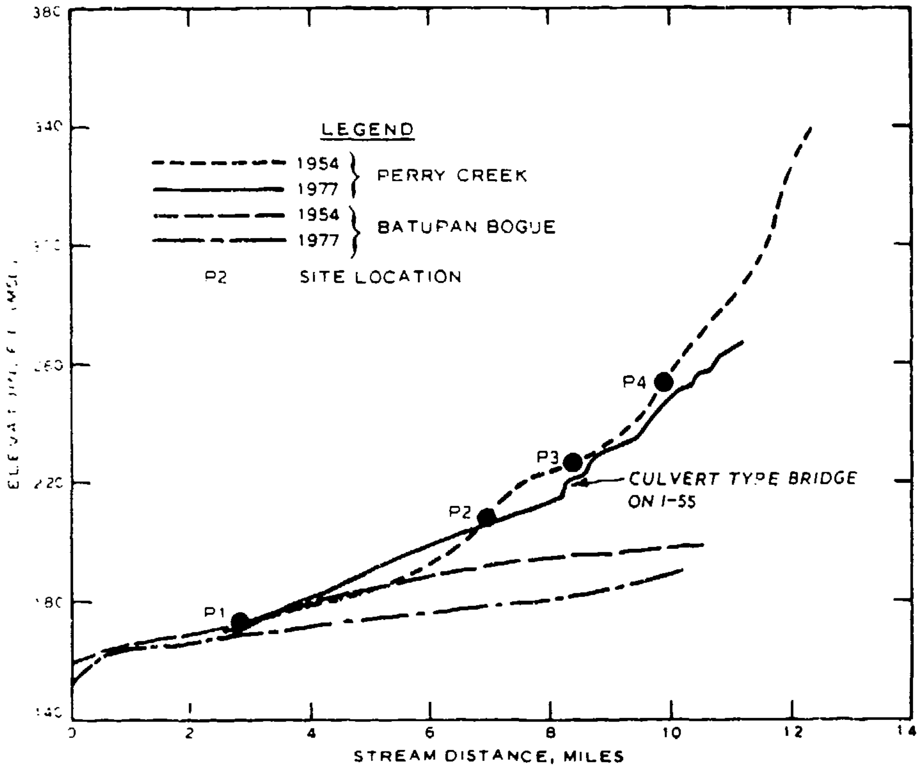

Figure 6. Longitudinal profiles of Perry Creek and Batupan Bogue showing channel degradation and knickpoint development (after Whitten and Patrick 1981)

knickpoint is usually dependent upon the occurrence of erosion-resistant materials in the channel which, at least temporarily, prevent the degradation or downcutting of the channel. These materials may either be a part of the alluvial fill or a part of the underlying soils or rocks. Basically, the occurrence of knickpoints is dependent upon stratigraphic or other types of inhomogeneities in the channel fill or underlying materials.

39. Knickpoints are caused by conditions which result in the erosion of the stream channel, that is, channel degradation. The parameters which describe the geometric and discharge characteristics of stream channels and which, when interrelated, permit an understanding of channel degradation are given below.

W = stream width (L)

D = stream depth (i.e., water depth) (L)

s = stream gradient (L/L)

Mw = meander wavelength (L)

S = sinuosity units

Qw = water discharge, L^3/T

Qs = sediment discharge, L^3/T

40. Schumm (1977), on the basis of field and flume studies, has described empirical relationships between these parameters as shown in the proportionalities given below.

$$Qw \sim \frac{W \times D \times Mw}{s} \text{ , Proportionality 1}$$

$$Qs \sim \frac{W \times s \times Mw}{D \times S} \text{ , Proportionality 2}$$

41. The examination of Proportionalities 1 and 2 reveals that channel depth D is increased when water discharge Qw is increased and is decreased when sediment discharge Qs is increased. Therefore, as would be expected, channel degradation and the resulting formation of knickpoints may be caused by increased water discharges which are not accompanied by increased sediment discharges. At constant water discharge, an increase in channel gradient S will also produce an increase in channel depth and, in turn, a knickpoint (Proportionality 2). Increases in channel gradient may be caused by changes in baselevel such as a lowering of sea level which, for example, accompanied Pleistocene glacial advances and, more importantly, by naturally occurring cutoffs of meanders and by channelization or straightening of channels (Whitten and Patrick 1981).

42. A knickpoint is a relatively nonpermanent feature whose position or location depends upon the relative erosion-resistance of channel materials and their response to discharge conditions. Given a sufficiently high discharge, a given knickpoint can be eroded away and a new knickpoint will be formed some distance upstream at a location which is again dependent upon relative erosion-resistance of channel materials. Also, a stream channel may exhibit a number of knickpoints along its longitudinal profile. The upstream displacement of the knickpoint is termed "headcutting." The relative rate of headcutting is variable; however, if water discharges are sufficiently high, the headcut may proceed upstream at rates of several hundred meters over several

hours or days. Ultimately, a headcut may proceed upstream throughout the upstream tributary system. When the channel materials are homogeneous in terms of erosion resistance, a headcut may proceed upstream throughout the basin without producing a knickpoint. A consequence of channel degradation and headcutting is the over-steepening of the channel banks resulting in progressive bank failure (Whitten and Patrick 1981).

Knickpoints in Spillway Channels

43. Mechanically, the origin of knickpoints in unlined emergency spillway channels will be similar to that of natural stream channels. The similarity is apparent when one considers that the outlet of the spillway is usually a natural channel and that the emergency spillway and its outlet may exhibit various changes in gradient naturally or through design. Figure 7 shows the stairstep development of knickpoints in the spillway at Saylorville as the result of the 1984 overflow event. Indeed, most dams exhibit similar changes in spillway gradient and usually a distinct knickpoint is located where the constructed portion of the spillway intersects the natural topography. At this point, a distinct waterfall will occur during spillway flow. Similar situations exist at the downstream end of concrete lined flood control channels. Furthermore, the erosion produced at this waterfall or at others along the outlet may be such that headcutting will proceed up the spillway channel, removing the waterfall in the process, until it can be at least temporarily stabilized by the presence of resistant materials which will produce a "new" waterfall. As in natural stream channels, the formation of the waterfall is dependent upon erosion-resistant materials in the emergency spillway channel and outlet. Again, discontinuities and inhomogeneities are critical factors affecting the location of knickpoints and headcutting.

a. Upstream view

b. Downstream view

Figure 7. Photographs showing severe erosion in the emergency spillway channel at Saylorville after the 1984 overflow event. Note stairstep erosional pattern (aft - Cameron et 1. 1986)

PART III: ANALYSIS OF FIELD DATA

Overview

44. Previous investigations (Cameron et al. 1986) have demonstrated that discharges (flows) are capable of producing extensive erosional damage and morphological change in unlined emergency spillway channels and that the damage and change must be related, in some fashion, to the nature and type of rock in the spillway and to the hydrology and hydraulics of the spillway channel discharges. Also, such extensive erosion must, of necessity, have some degree of impact on downstream reaches by the introduction and deposition of sediments there. However, these findings have not been quantified in terms of cause and effect nor in terms of judging relative damage among sites which have experienced erosion. Thus, there is a need to identify one or more factors which will quantify the response of the channel to erosional forces and, having identified the factors, determine cause and effect relationships with other factors or variables which may effect or control the erosional system.

45. For the purposes of this discussion, emergency spillways are composed of two parts--(a) the upstream portion which consists of the spillway crest and that portion which is excavated, and (b) the downstream portion or outlet which extends from the downstream end of the excavated sect on to the main river channel (Figure 8). During spillway flow, vertical degradation is initiated in the downstream portion of the spillways, knickpoints are developed or made more pronounced, and knickpoint migration (headcutting) advances upstream into the excavated section toward the crest thereby threatening the dam (see Part IV). The result of these processes is a demonstrable morphological change in the geometry of the spillway.

Spillway Flow Data Bases

46. Data bases composed of spillway flow case histories for Soil Conservation Service (SCS) and CE dams were studied and evaluated as a part of the REMR investigations for the purpose of idertifying significant or key factors for quantification of damage (response) in terms of flow or other variables. The spillways of both SCS and CE dams were excavated in rock. The CE dams, in comparison to those of the SCS, are large with a relatively high degree of hydraulic conservatism built into their spillways. Thus, a small

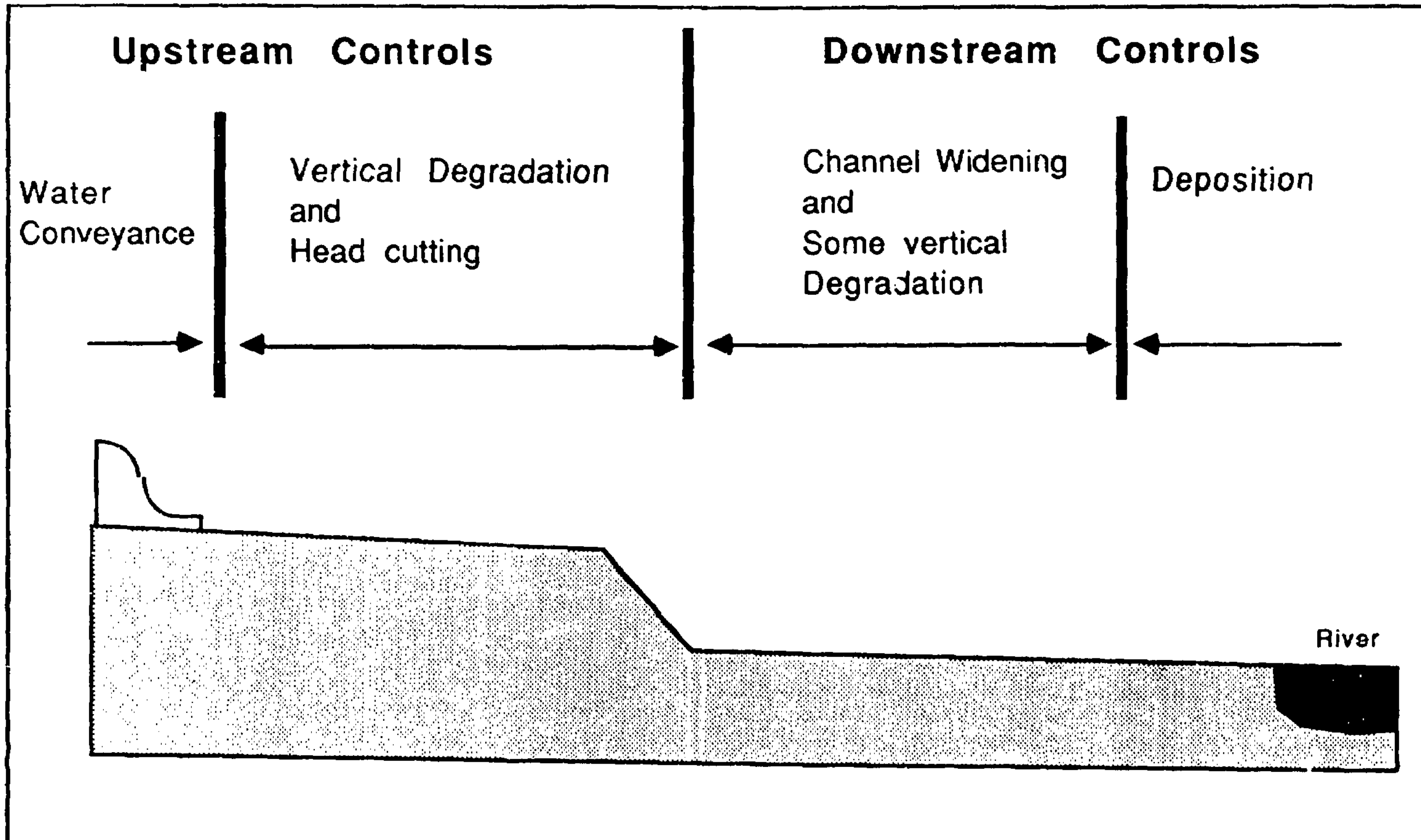

Figure 8. Diagramatic cross section of emergency spillway and excavated channel showing upstream and downstream sections, major processes acting along the longitudinal section and parts of the spillway channel

percentage of the CE spillways have experienced erosion and a statistically sufficient data base would not be available if only CE dams were included. Even so, the erosion that did occur in CE spillway channels tended to be significant. The smaller and more numerous SCS dams provide more examples of spillway flows than do the CE dams. The SCS Emergency Spillway Flow Study Task Group (ESFSTG) has compiled a data base giving all available data on the nature of the spillway flow, channel response, and information on the site and provided these data to the REMR study group. The majority of the data in the data bases comes from two SCS studies--one in Arkansas and the other in Kentucky (Soil Conservation Service 1982, 1984*). Although data at other sites in other areas are available, they are not as complete in terms of geologic information as the Arkansas and Kentucky studies. The data base created by the combining of SCS and CE data is similar to the reconnaissance data base given in Cameron et al. (1986) but differs in two ways: (a) the combined data base contains more detailed information concerning flows, site conditions, and geomorphic information and (b) there are significantly more data entries with the addition of non-CE dams. The combined data base includes 35 examples of spillway flow which have been organized into two main categories of hydraulics and channel geometry. Of the 35, 16 were of sufficient detail for analysis and comparative study and, of these, two were CE dams. The data base is given and defined in the Tables 1-3.

Hydraulic parameters

47. The hydraulic parameters, peak flow, cumulative flow, hydraulic attack, flow duration, flow depth, and maximum velocity, given in Table 1, are measures of the hydraulic forces operating on the spillway during the flow event. The examination and comparison of these parameters reveal a wide range of values and rather poor correlation among the values; that is, a given site exhibiting the highest peak flow does not necessarily exhibit the highest velocity or cumulative flow. For this reason, the parameter, hydraulic attack, was developed by the SCS (Soil Conservation Service 1973). The parameter is expressed as:

$$\frac{Qe}{b}$$

* Soil Conservation Service. 1984. "Kentucky Spillway Performance Report," Unpublished report, Emergency Spillway Flow Study Task Group, Engineering Division, Soil Conservation Service, US Department of Agriculture.

where

O_e = total volume of outflow through the earth spillway during passage of the freeboard hydrograph in acre-feet

b = bottom width of the earth spillway in feet

48. The SCS derived this parameter to provide an assessment of the hydraulic forces that were applied to the spillway channel during the flow event. The term serves to incorporate volume, duration, and depth of flow, and is used to normalize flows at different sites, thereby allowing comparisons of the amount of attack between sites. The durations of flow at Grapevine and Saylorville were significantly higher than those of the SCS dams as well as for many CE dams.

Geometric parameters

49. The geometric parameters include those parameters which are a part of the design of the spillway. Of these, the inflection points or knickpoints between the excavated and steep sections may be of greater importance than the channel width, excavated length, length of steep section, gradients, or elevation drops. On the basis of observational data from CE and SCS dams, vertical degradation often begins where the spillway channel gradient changes--that is, at an inflection point or knickpoint. These relationships are shown in Figure 9 for Grapevine and Saylorville reservoirs. At this point, the spillway channel changes from an excavated section with a uniform relatively low gradient and wide bottom to one of a nonuniform, steeper gradient and no excavated channel.

Erosional damage parameters

50. The erosional damage parameters, total volume eroded, excavated volume eroded, unit volume eroded, failure volume, and horizontal gully recession, as indicated previously, are measures of the response of the spillway channel to erosional processes at work during the flow event. The failure volume is a postulated volume of material that would be eroded if channel or gully degradation extended through the excavated section (Table 3).

Ranking of Spillway Response to Emergency Flow

51. Previous evaluations of flows in emergency spillways have addressed the severity of the channel response in terms of a qualitative perception of how badly the reservoir structure was threatened (Scanlon et al. 1983 and Cameron et al. 1986). Thus, in regard to CE dams, the perceived threat to the

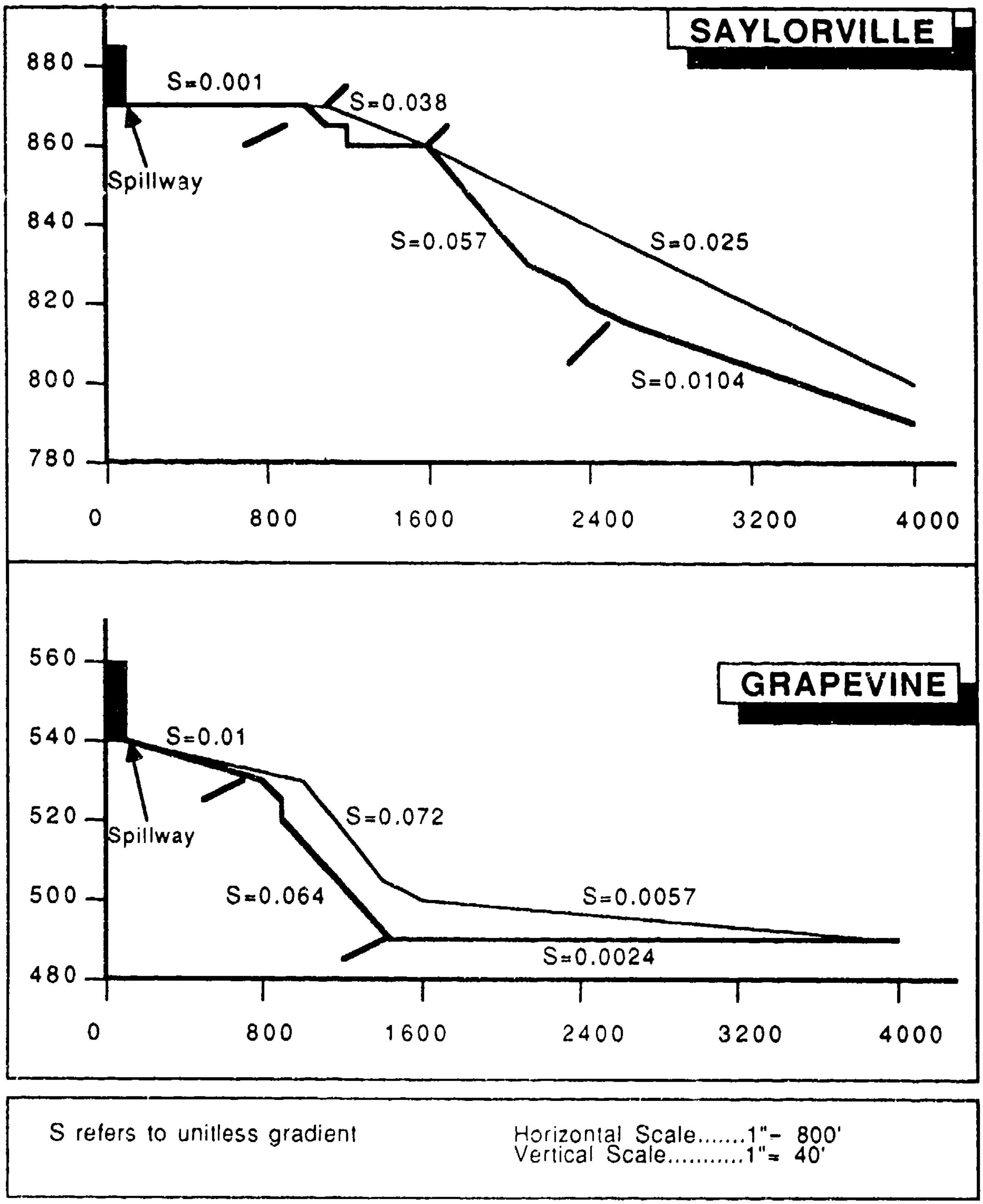

Figure 9. Preflow and postflow longitudinal profiles

structure at Grapevine was greater than that at Saylorville since erosion occurred nearer to the spillway structure at Grapevine than to Saylorville, even though the flows and generalities of the channel response were similar. Granting that this perception is an important consideration when evaluating sites, it does not address the issue of quantifying the response of the channel to the emergency flow. Therefore, there is a need to devise quantitative criteria for comparing the changes in channel morphology at different sites which have experienced flow events. The evaluation of information in the CE and SCS data base resulted in the identification of two criteria which are considered to be measures of the response of the channel to the hydraulic forces applied; these criteria pertain to the volume of material eroded and distance of headward erosion.

Volume eroded

52. The volume of material eroded during the flow event was calculated for each site in the data base. The calculations were performed using preflow versus postflow data including longitudinal profiles, transverse cross sections, and topographic site maps. Figure 10 shows the relative volumes of material eroded for sites in the data base; these volumetric data have been normalized by dividing the excavated volume eroded by the width of the spillway channel. Figure 10 demonstrates that the CE spillway channels have experienced significant amounts of erosion.

Volumetric ranking

53. The data in Figure 10 provide insight to the relative amount of erosion which has occurred at a given site but do not yield sufficient information in regard to the severity of that erosion. A more useful measure of volumetric erosion would be one which compares the actual amount of erosion to that amount of erosion which would cause failure of the spillway. Spillway failure would occur by the headward migration of the gully formed at the knickpoint or deflection point between the upstream excavated and downstream steep sections as shown in Figure 11. Note the occurrence of gully mouth stability; this phenomenon is most likely caused because the geometry of the gully has equilibrated to that particular spillway flow. Gully mouth stability is also influenced by the presence of resistant layers in the spillway channel. Therefore, the Volumetric Ranking is defined as:

$$\frac{\text{Excavated volume eroded, cu ft}}{\text{Calculated failure volume, cu ft}} \times 100$$

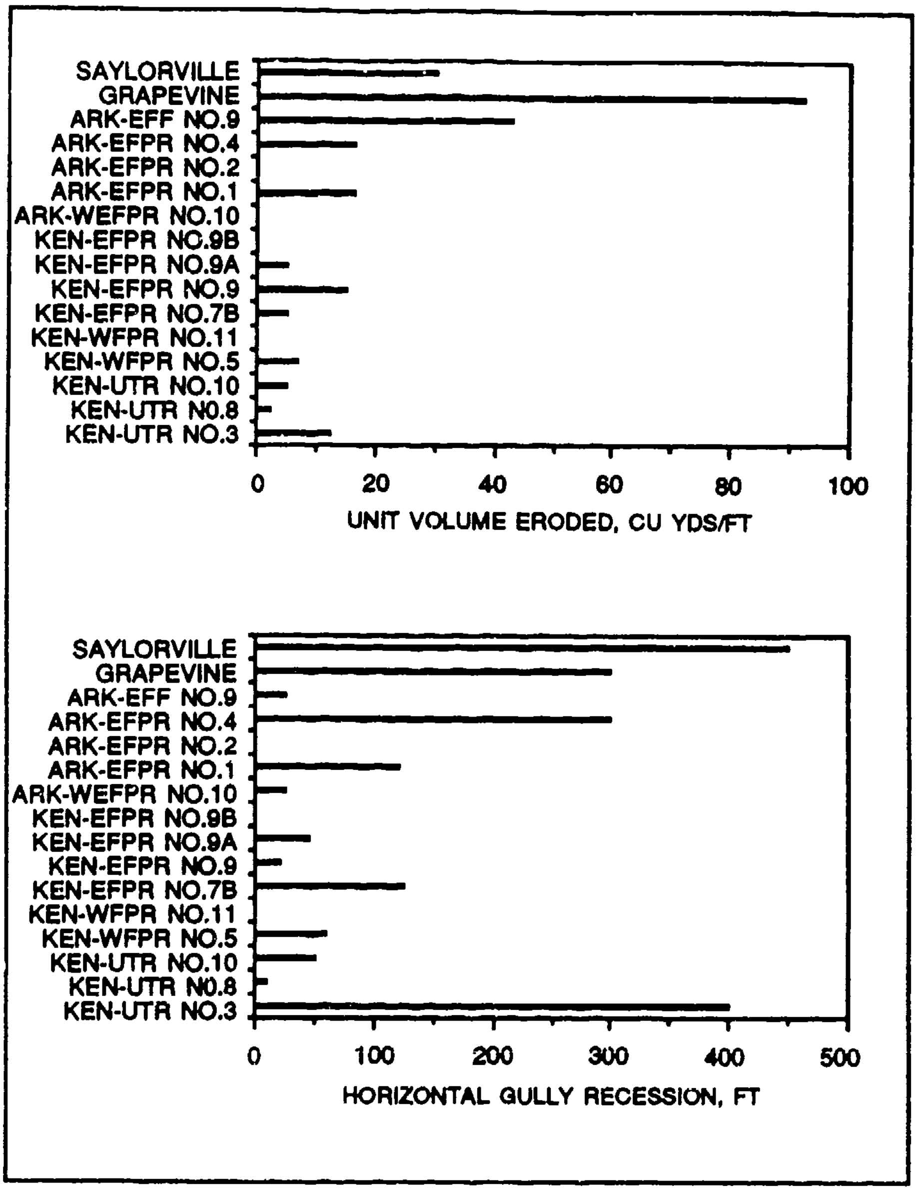

Figure 10. The erosion parameters, volumetric erosion, and horizontal erosion, shown for the 16 sites that calculations were made. Note the discrepancy between CE dams and SCS dams in the upper part of the figure

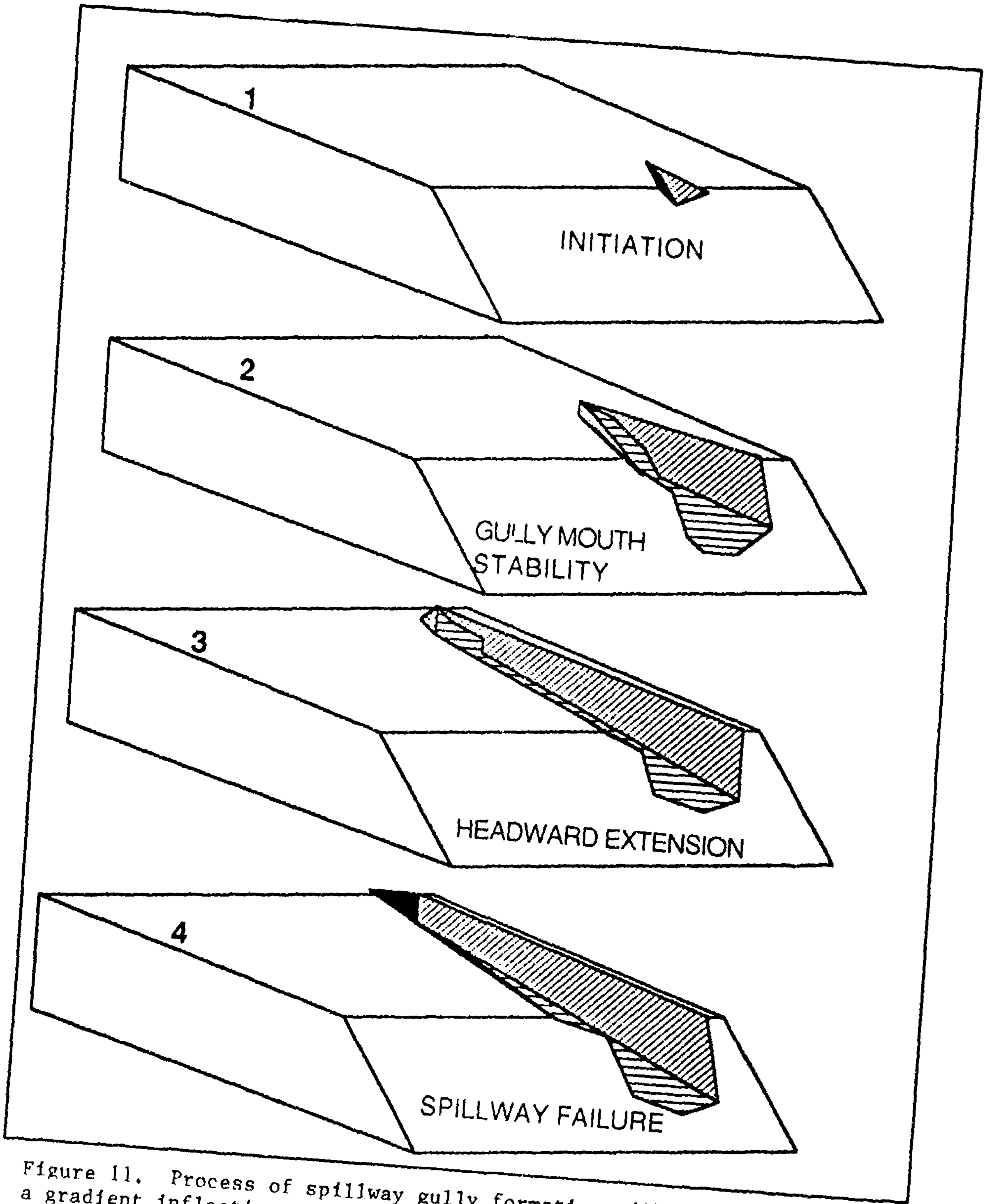

Figure 11. Process of spillway gully formation--(1) Erosion begins at a gradient inflection; incisement and headward extension are the dominate processes. (2) Gully mouth has reached equilibrium and is no longer enlarging. The only erosion taking place is at the head of the gully with some gully widening. (3) Headward erosion. (4) Headward erosion undermines the spillway structure and failure occurs

54. The calculated failure volume is determined by extending the actual eroded gully upstream to the spillway weir and measuring the volume of material included in the extended gully. Figure 12 illustrates examples of actual gully morphologies at seven SCS and two CE sites; Figure 13 is an example of the extended gully and the method of calculating volumetric erosion ranking. The calculated failure volume is merely an approximation of a hypothetical condition which would result in failure of the spillway. Thus, the calculated failure volume does not include the total volume of potentially erodible material lying above the flood plain and below the weir but a portion of that volume whose actual dimension would be dependent upon the size of the gully developed in the material. That is, spillway failure would occur long before the potentially erodible material was entirely removed.

55. The determination of the size of the extended gully is based upon two models which are, in turn, based upon the gully dimensions. The small gullies are 6 to 15 ft* deep at the mouth and are 30 to 40 ft wide; the large gullies are 15 to 30 ft deep at the mouth and are 75 to 100 ft wide. The SCS and CE dams are represented, respectively, by the small gully model and large gully model. Figure 14 illustrates gully morphologies for the two models.

Volumetric erosion

56. Table 4 (column 2) shows the calculated volumetric erosion rankings for the dams in the data base. The CE dam, Saylorville, exhibited the highest ranking, followed by EFPR No. 4, and Grapevine. Although the CE dams generally rank high, two SCS dams, EFPR No. 1 and WFPR No. 5 rank greater than 20 percent. On the basis of these data, one would suspect that Saylorville was slightly nearer to failure than Grapevine in terms of volumetric erosion.

Horizontal erosion

57. The horizontal distance that the erosion progresses toward the spillway structure is another criterion for analyzing the erosion that took place during spillway flow. The horizontal erosion values for dams in the data base are given in Figure 10. These values do not need to be normalized and are independent of the spillway width. Although Saylorville exhibited the greatest horizontal erosion, there is one SCS dam which exhibited horizontal erosion values greater than that of Grapevine. Generally, the CE and SCS dams were more similar in terms of horizontal erosion than volumetric erosion.

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* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 3.

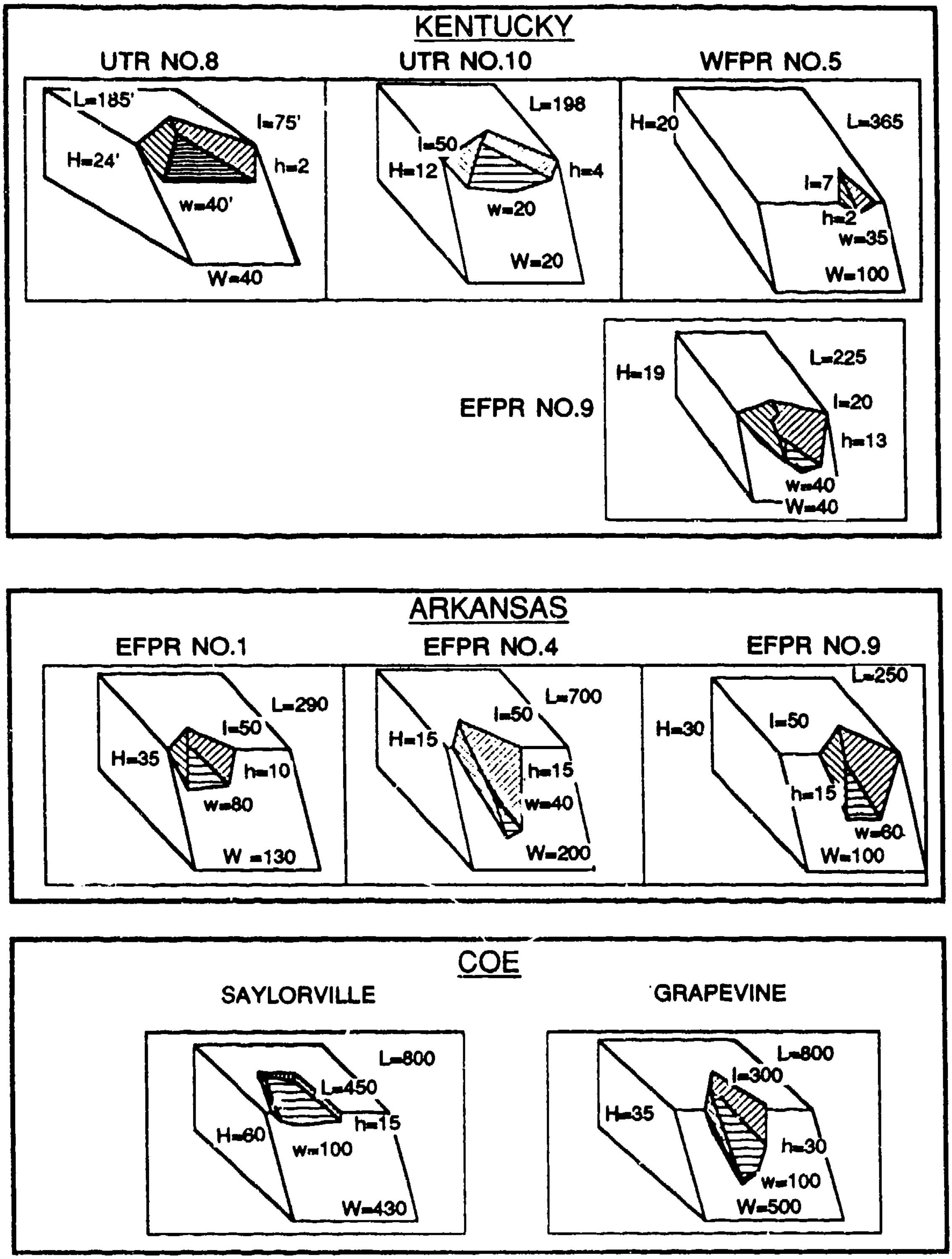


Figure 12. Channel morphologies produced by erosion at typical spillways. All units are in feet, but the block diagrams are not to scale

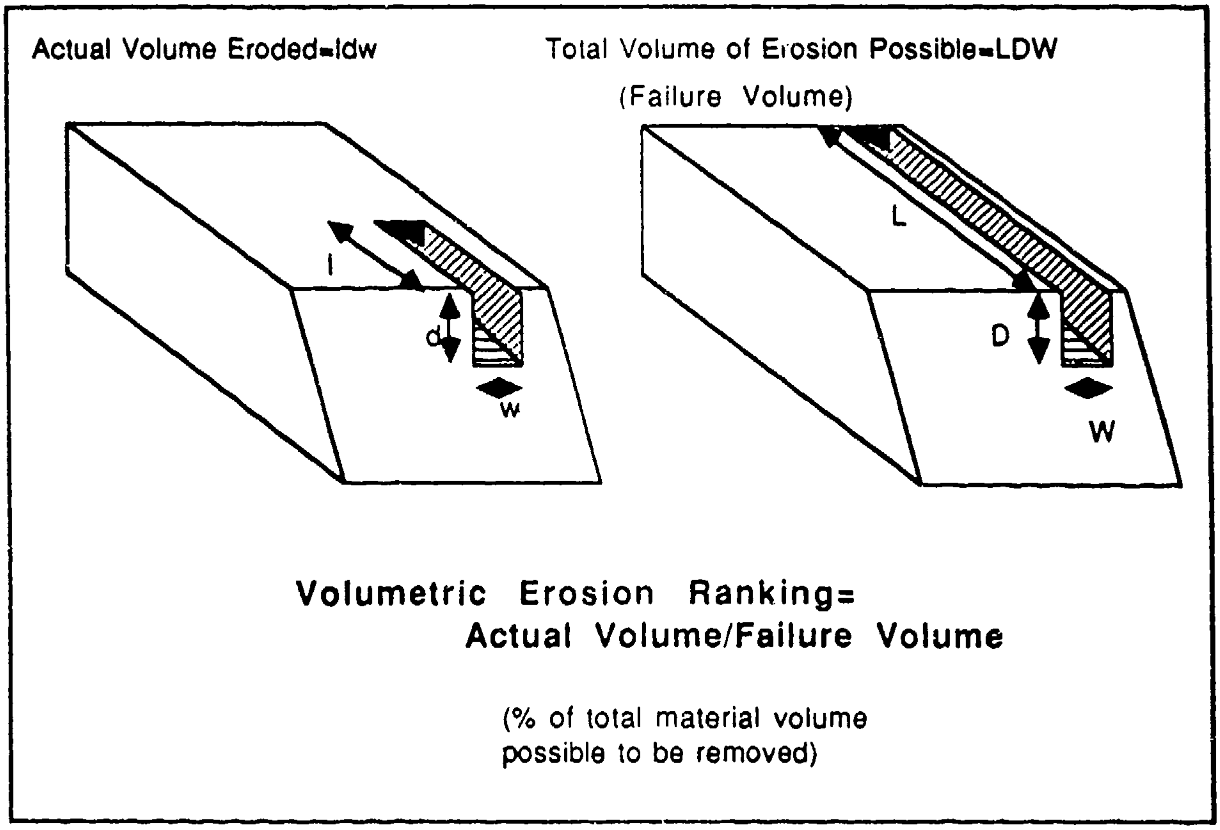


Figure 13. Illustration showing means of determining volumetric erosion ranking

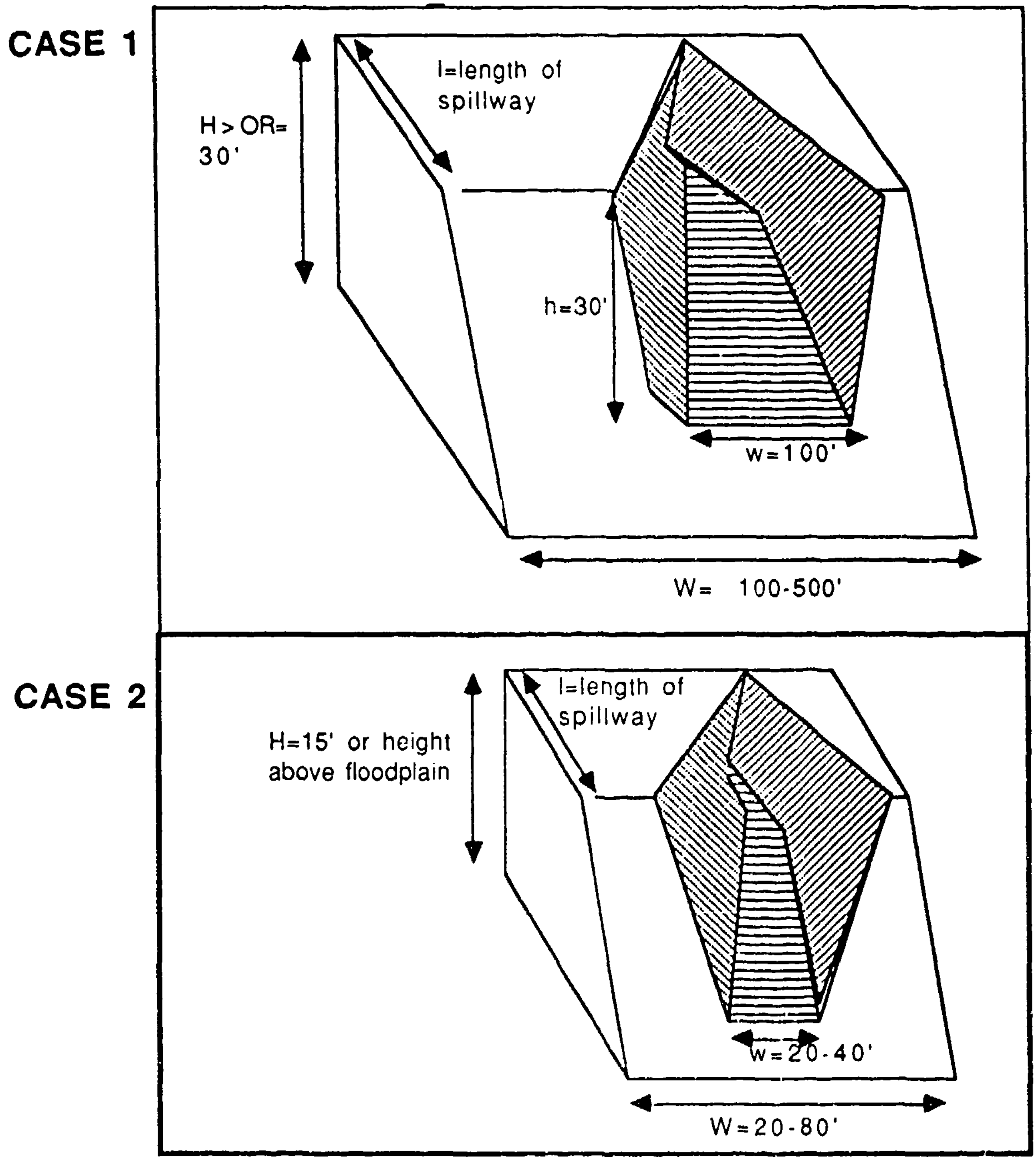


Figure 14. Volumetric erosion model for large and small dams showing equilibrium gully mouth areas

Horizontal erosion ranking

58. Horizontal erosion may also be expressed as a ranking, namely:

$$\frac{\text{Horizontal erosion, ft}}{\text{Length of excavated section, ft}} \times 100$$

59. This parameter is a relative measure of how near the gully encroached upon the weir or crest of the spillway. Figure 15 gives an example of the calculation of this parameter. Horizontal erosion rankings are given in Table 4. These data show that five SCS dams, UTR No. 3, WFPR No. 5, EFPR No. 7B, EFPR No. 1, and EFPR No. 4 have higher rankings than either Grapevine or Saylorville. Generally, these high horizontal erosion rankings occurred at dams where the gullying was very shallow and, therefore, most likely did not threaten the structure.

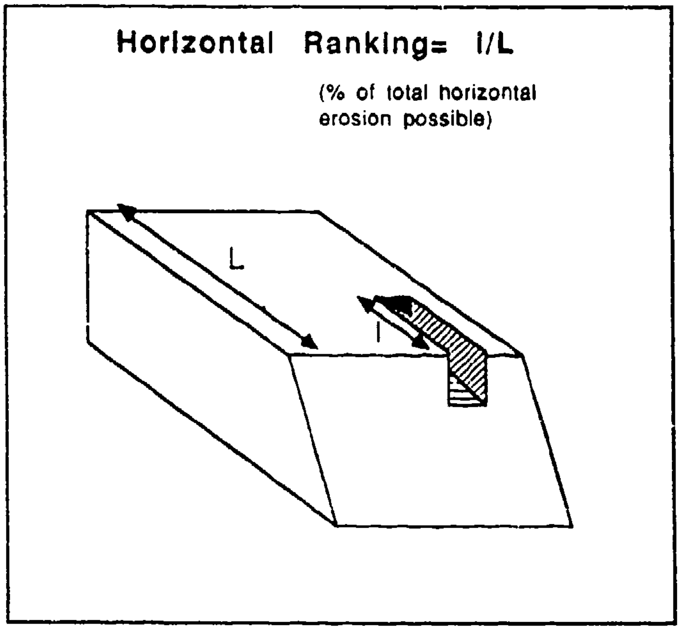


Figure 15. Example of procedure for determining horizontal erosion ranking

Comparison of volumetric and horizontal erosion

60. A plot of volumetric versus horizontal erosion rankings given in Table 4 is illustrated in Figure 16. The plot allows for a visual comparison of the relative type and amount of erosion occurring at each site in the data base. Three fields with arbitrary boundaries have been delineated on the plot

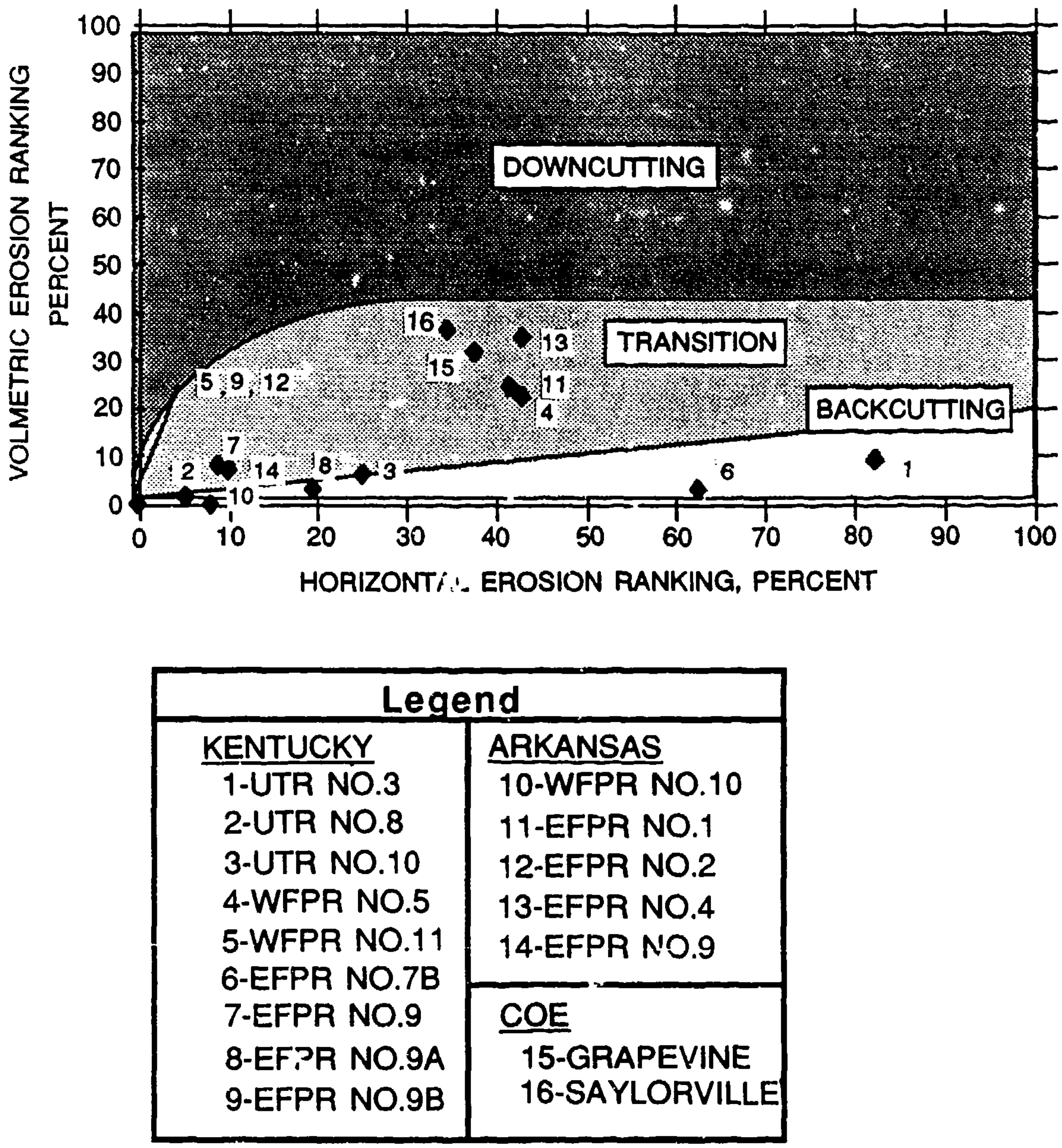


Figure 16. Generalized erosional behavior at various dams. Differences in the behavior is due to spillway channel geometry and site geology

to identify sites exhibiting downcutting, backcutting or recession, and transitional characteristics between downcutting and backcutting. The plot shows that, for six sites, horizontal gully recession without significant gully deepening is the more prevalent phenomenon. Seven sites exhibited transitional characteristics, and none of the sites exhibited significant downcutting.

61. The explanation of the data plotted in Figure 16 and shown in Table 4 rests primarily on the presence of structural and stratigraphic discontinuities underlying the spillway structure. These data support the contention that erosion-resistant strata underlying the spillway control downcutting, and when present at shallow depths, result in horizontal erosion and recession of the gully towards the spillway crest. Regarding dam safety and the threat at given sites--those sites exhibiting transitional characteristics should be viewed as most serious since the possibility exists that deep gullying may occur which could undermine the spillway crest.

Correlations of Volumetric and Horizontal Erosion Rankings with Hydraulic and Geometric Parameters

62. Having shown that the volumetric and horizontal erosion rankings are measures of the extent of erosion to which a spillway has been subjected, we must now determine what relationships may exist between these rankings and the hydraulic and geometric parameters previously described and given in Tables 1 and 2. The determination of these relationships was accomplished by conducting linear and polynomial regression analyses in which each individual volumetric and horizontal erosion ranking was compared with each hydraulic and geometric factor. Linear and polynomial regressions were calculated for the data base exclusive of and including CE dams. Correlation values (R-squared) for the SCS dams are given in Table 5 and those for the combined SCS-CE data base are given in Table 6.

63. The following observations and conclusions summarize the data in Tables 5 and 6.

- a. Overall, there is only minor statistical significance among the attempted correlations.
- b. The R-squared values for polynomial regression analyses were higher than those for linear regression analyses. Also, most of the polynomial regression curves exhibited maxima or minima.

c. Although the highest R-squared value (0.79) cccurred for the comparison of volumetric erosion ranking versus steep section length for the SCS dams, the R-squared values for the combined SCS-CE data base were higher.

d. The R-squared values for attempted correlations in both data bases (exclusive and inclusive of CE dams) involving the geometric parameters were somewhat higher than those involving the hydraulic parameters including hydraulic attack.

64. The geological and hydrological significance of the regression analyses is thus:

a. The absence of overall significant statistical correlation among variables may be ascribed to variable geological conditions, particularly the nature of discontinuities, among the sites in the data base. Structural and lithostratigraphic discontinuities were not addressed in the variables used in this study.

b. The regression analyses reveal that the hydraulic parameters pertaining to various aspects of flow, water depth, and velocity are not important primary measures for predicting the nature and extent of erosion at a given emergency spillway excavated in rock; however, these parameters should be important in predicting erosion in noncohesive soils and sediments.

c. The somewhat higher R-squared values of correlations involving geometric as opposed to hydraulic parameters support the notion that the presence of knickpoints along the longitudinal profile of the upstream and downstream sections of the spillway channel is an important factor in the initiation of erosion and degree to which erosion will occur.

d. The occurrence of maxima and minima on polynomial regression curves suggests that the erosional phenomena operating at these sites are governed by the concept of geomorphic thresholds.

65. These apparent relationships will be addressed further in Part IV, regarding laboratory investigations and in which the significance of geometry and thresholds is developed from flume experiments.

PART IV: LABORATORY INVESTIGATIONS

66. The occurrence of knickpoints and headcutting may be effectively investigated by means of moving-bed, circulating flume tests. An early study by Brush and Wolman (1960) using a 4-ft-wide, 52-ft-long flume with uniform, homogeneous, noncohesive bed material in which an artificial knickpoint was made prior to introduction of flow yielded information regarding the erosion occurring upstream, along, and downstream of the oversteepened reach. The information from these flume studies was interpreted in terms of five hypothetical geologic models which represented various conditions of resistant and nonresistant bed material; these conditions are shown in Figure 17.

67. Type A shows that the final eroded gradient will approach the average initial channel gradient. Type B represents a resistant stratum intersecting the channel upstream of the knickpoint at an arbitrary angle of intersection. This example would be typical for regions underlain by folded sedimentary rocks. The knickpoint will move upstream until it intersects the resistant stratum; the rate of erosion will be decreased and the resistant bed will preserve a steep slope along the profile. The break in slope will be present until the resistant bed is removed. Type C shows a situation where a resistant layer is positioned horizontally over a less-resistant layer. In this example, the slope below the knickpoint may increase toward the vertical if there is a large difference in the resistance of the capping material and underlying material. Type C is the most important in terms of erosion in emergency spillways because of the potential for rapid migration of the knickpoint and potential structural failure. Types D and E are variations of the three preceding examples.

68. Brush and Wolman (1960) offer the following conclusions regarding the formation and migration of knickpoints:

- a. Knickpoints will flatten out quickly if the stream has homogeneous bed material and are capable of transporting this material easily.
- b. Resistant material near the original site of a knickpoint would tend to preserve the knickpoint and localize the change in slope and a break in the longitudinal profile would be expected at the point of change in bed material with or without the prior initiation of knickpoint downstream.
- c. A knickpoint will not easily migrate past a very resistant layer.

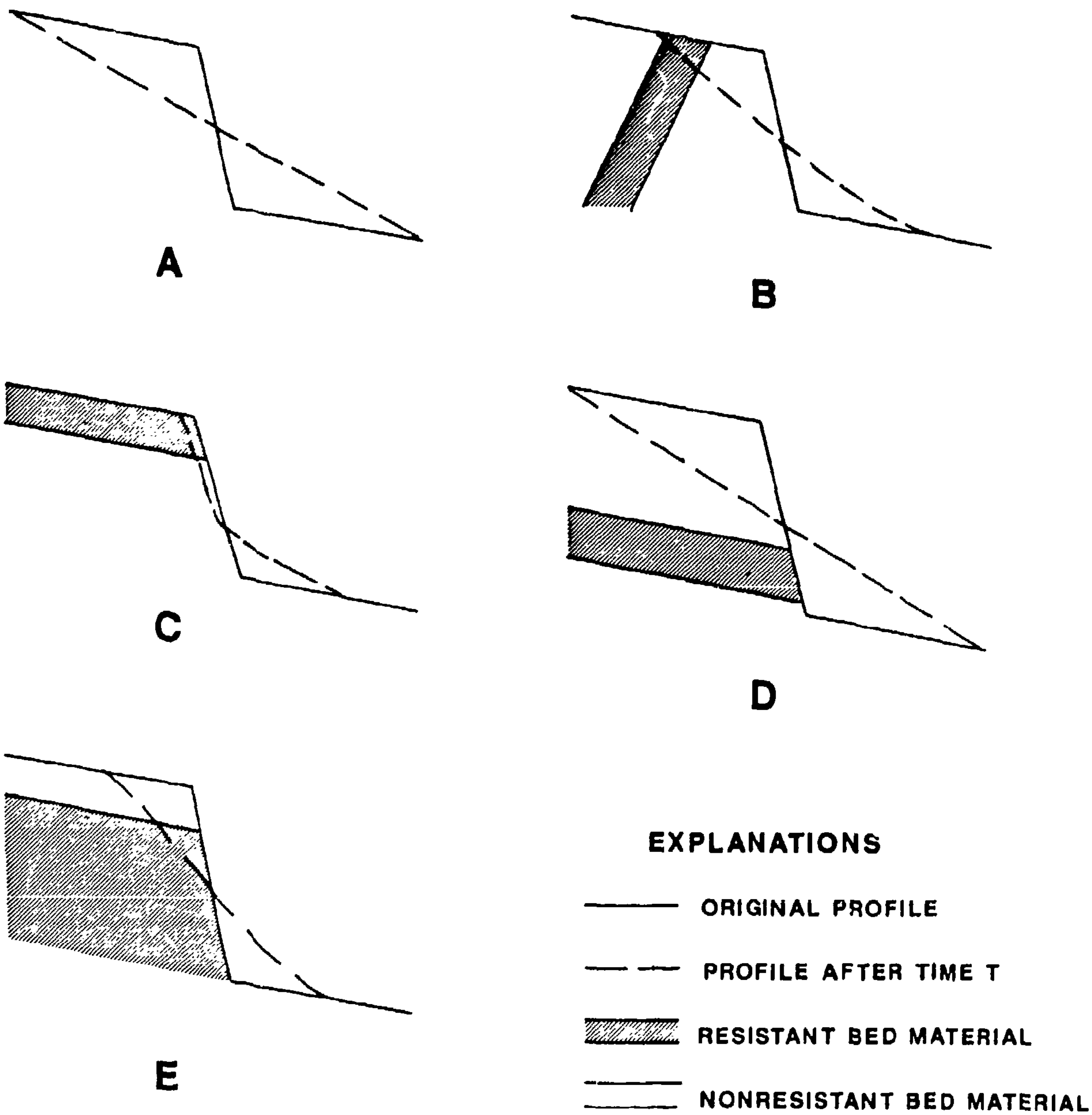


Figure 17. Hypothetical geological models representing resistant and nonresistant bed materials (after Brush and Wolman 1960)

d. Waterfalls are a special case where the steep slope is caused by undermining of more erodible underlying material.

69. Recent investigations reported by Schumm, Mosley, and Weaver (1987) have addressed techniques for mathematically modeling knickpoint initiation and migration on the basis of flume and similar experiments; however, these studies were generally restricted to uniform bed material and have not involved discontinuities.

Flume Studies

70. On the basis of the special significance of waterfalls in the erosion of unlined emergency spillways, flume studies were conducted as a part of the REMR investigations using a 16-ft-long, 1.5-ft-deep, and 1-ft-wide recirculating, tilting flume in which a waterfall was constructed of simulated stratified earth materials (gravel-gelatin mixtures). The Froude Numbers for the flume experiments ranged from 1.2 to 1.5 and the average value was 1.4; these values are similar to those given in Table 1 for SCS dams in Kentucky. The flume is illustrated in Figure 18. These flume studies are ongoing and are the subject of Report 4 of this series (May, in preparation).

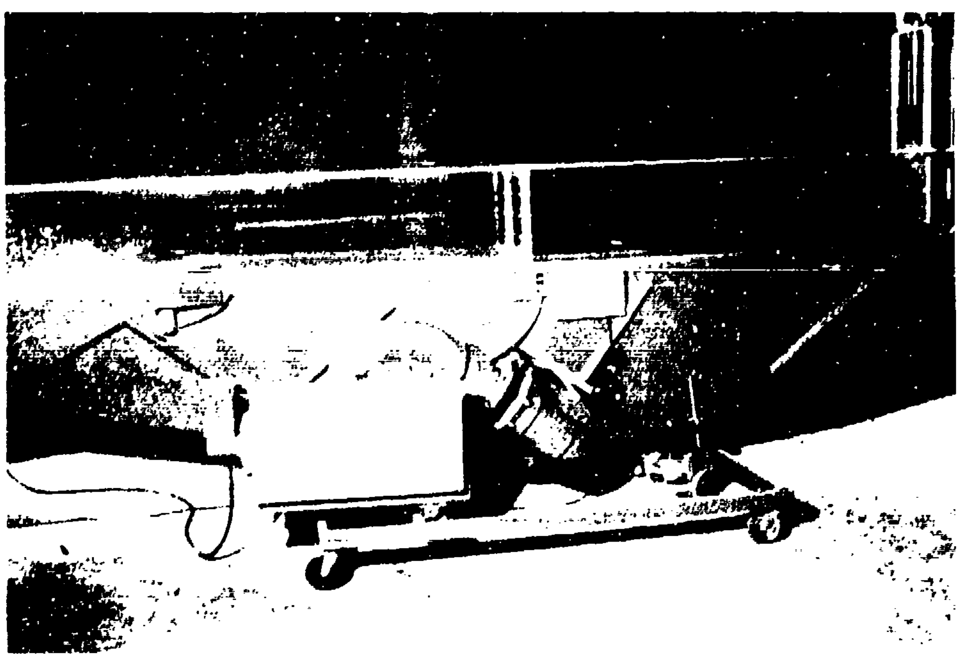


Figure 18. Photograph of the recirculating flume

71. The flume experiments show that headward erosion of a knickpoint is generally controlled by the following interrelated factors and/or conditions: (a) stratigraphy of the rocks forming the knickpoint or waterfall, (b) ratio of the height of waterfall (Z) to the depth of the water (Y), (c) tailwater conditions, (d) venting condition of the waterfall, and (e) location or position on hydrography describing the discharge event. These factors and conditions are described below.

a. Headward erosion is enhanced by the occurrence of interstratified layers of hard and soft (erodible) rocks at the waterfall.

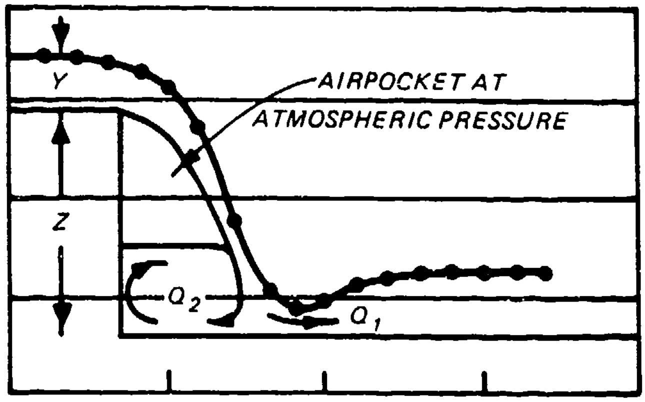
b. In a typical, vented drop structure, maximum dissipation of energy occurs when the ratio Z/Y is greater than approximately 8/1 since the distance from the base of the falls at which the water (nappe) strikes is inversely proportional to this ratio. Maximum dissipation of energy in a drop structure would be similar to maximum energy for erosion at a waterfall, other factors being the same. The height Z is dependent upon the stratigraphic thickness(es) (Figure 19).

c. Maximum erosion occurs when the tailwater height is minimized.

d. The discharge over a waterfall produces a "reverse roller," Q2 in Figures 19 and 20, which is the principal mechanism causing erosion. The airpocket behind the waterfall may be either vented (Figure 19) and at atmospheric pressure or unvented (Figure 20) and at a pressure less than atmospheric. When conditions are unvented, the low pressure in the airpocket behind the nappe draws the reverse roller against the face accelerating erosion there. The flume experiments demonstrated that an initially vented waterfall became unvented during discharge increases, when the airpocket is replaced by water. Also, when discharge decreased, a low-pressure zone developed behind the waterfall, entraining air bubbles which coalesce to form an airpocket. These pressure differences drew the reverse roller onto the face of the waterfall producing erosion. These effects were found to be true even when the ratio, Z/Y , was less than 8/1 and suggest that the venting condition may be of greater significance than Z/Y .

e. Using hypothetical flood hydrographs (analogous to emergency spillway discharge events), these findings indicated that certain erosion "windows" occurred as a result of stratigraphy and its influence on knickpoint height. Figure 21a illustrates the scenario observed in the flume experiments for a vented waterfall. As velocity and discharge increased rapidly, the waterfall moved further from the face and erosion ceased. However, a slow decrease in discharge resulted in a resumption of knickpoint erosion. The erosional activity on the declining line of the hydrograph was observed to be more pronounced than the first because of the additional time involved. Figure 21b shows the overall relation between venting condition and time; namely, that the unvented condition leads to more severe

Figure 19. Geometry of a vented waterfall



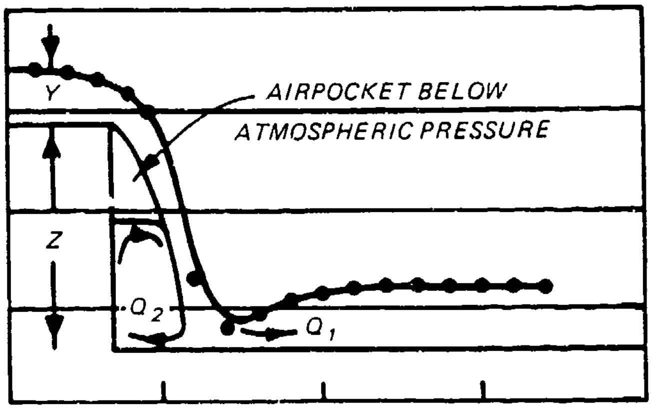
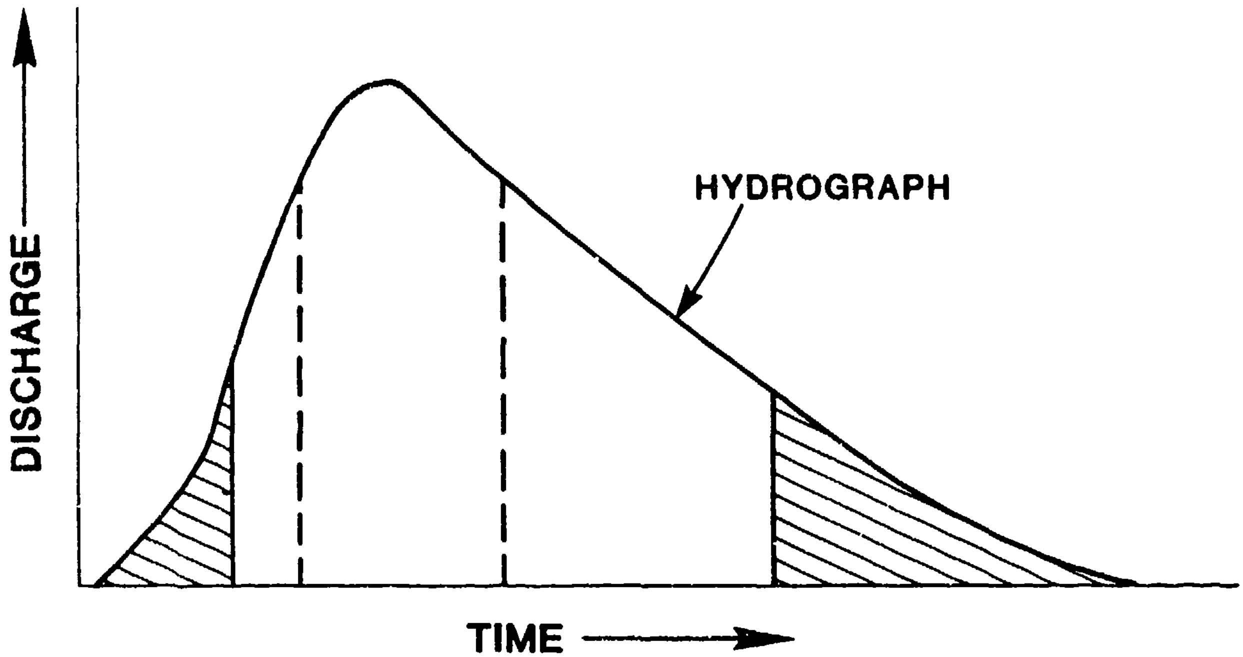


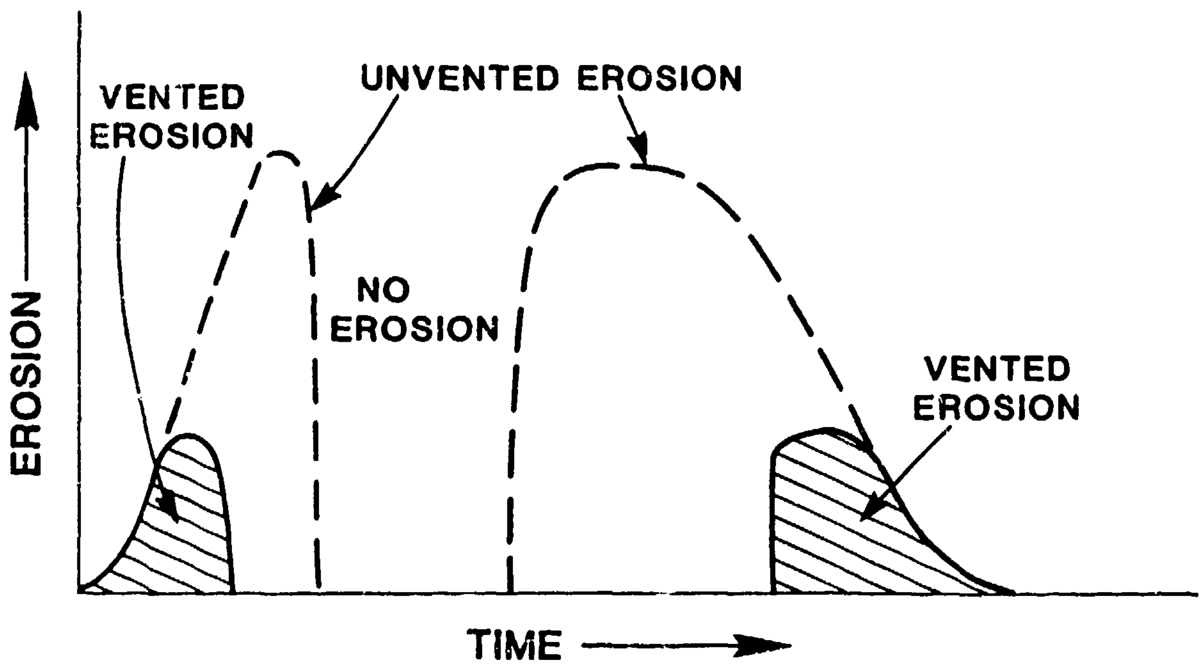
Figure 20. Geometry of an unvented waterfall showing the nappe and reverse roller drawn nearer to face (compare with Figure 19)

erosion over longer periods of time, and that peak discharge is not accompanied by erosion.

72. These preliminary findings indicate that the severity of erosion is dependent on the erodibility and thickness of the strata forming the waterfall, venting, and the hydrology of the overflow event. Table 7 summarizes the conditions which are conducive to erosion. Table 7 is a qualitative summary of the conditions which are conducive to the occurrence of erosion at waterfalls in emergency spillway channels in terms of Z/Y, venting, and hydrograph position. The unvented conditions were orders of magnitude more severe than the vented conditions in the flume studies.



a. Showing vented erosion (cross-hatched) on rising and falling limbs



b. Relationship between vented and unvented erosion versus time

Figure 21. Theoretical spillway discharge hydrograph (note window of nonerosion centered about peak discharge)

Discussion of Preliminary Laboratory Findings

73. The identification of windows or thresholds at which erosional processes are maximized was an unexpected outcome of the research, particularly so since one would suppose that the amount of erosion experienced would be proportional to the discharge, specifically the velocity accompanying the discharge, to which the channel was subjected. However, the concept of thresholds is not new in terms of fluvial geomorphological theory; specifically, Schumm (1973) advocated the concept that geomorphic processes were initiated at thresholds which could be either intrinsic or extrinsic. Examples of intrinsic thresholds include the buildup of sediment in a valley until the valley slope is increased to the point (threshold) that erosion is initiated or the progressive increase in channel sinuosity in deltaic areas until a cutoff occurs due to decreasing slope (threshold). An example of an extrinsic threshold would be the change in bed form as current velocity changes. The example of bed form change is important because it shows that the reaction is not necessarily progressive. In regard to the erosion of knickpoints in emergency spillways, the results of the flume studies exemplify extrinsic thresholds in that the channel is responding to the increased velocity to which it is subjected; furthermore, the response is not progressive.

74. As indicated in Table 7 the vented condition of the knickpoint (vented versus unvented) is a meaningful factor only when considered in terms of the ratio of the depth of water to the height of the waterfall which, in turn, is controlled by the local stratigraphy. However, having some idea of expected water depth and conducted geological fieldwork on the spillway, one could identify conditions which would be critical.

75. The identification of whether or not conditions in the field would be vented or unvented may be difficult to determine and would depend upon the geometry of the spillway channel and the topography of the outlet channel. Generally, vented conditions would prevail if, on the basis of geometry and topography, the face of the knickpoint was open to the air. Such would be the case in wide, topographically unconfined, areas in the outlet channel; however, such would probably not be the case near or in the more confined portions of the spillway channel itself.

PART V: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

76. The studies described herein dealing with field and laboratory investigations of the nature and causes of erosion of unlined emergency spillways have resulted in the following conclusions:

a. The erosional phenomenon occurring in the spillway channels is, from a geomorphological standpoint, similar to that which may occur in natural stream channels which, either through a lowering of baselevel or channelization, exhibit a knickpoint on their longitudinal profile. In either case, spillway channel or natural stream channel, gullying (headcutting) will proceed upstream through the channel accompanied by significant erosion and channel degradation.

b. Structural and stratigraphic discontinuities (including fractures, faults, joints, dip orientation, igneous contacts, and veins, as well as bedding planes, unconformities, bed pinch outs and facies changes), play a major role in the erosion of rock in unlined emergency spillway channels.

c. The location and geometry of channel gradient changes (knickpoints) which can occur as abrupt waterfalls, as a series of closely spaced "stairsteps," or as gentle, subtle changes, are often controlled by structural and/or stratigraphic discontinuities in rock masses.

d. Detailed engineering geological maps and cross sections which accurately describe and attempt to quantify the nature and distribution of discontinuities in the rocks underlying emergency spillway channels are essential to meaningful evaluation of erosion potential (particularly headcutting) at site-specific levels.

e. Spillway channels having experienced emergency flow may be evaluated and compared in terms of volumetric and horizontal erosion rankings. These parameters provide insight as to how serious the erosion threat to a particular dam is and may be used to give priority to remediation. Generally, horizontal erosion is more significant than volumetric since strata having varying degrees of erosional resistance usually underlie many spillways, thereby preventing serious downcutting and high volumetric erosion.

f. Comparisons of erosional rankings (volumetric and horizontal) with hydraulic and geometric aspects of spillway flow and spillway design using linear and curvilinear regression analyses indicate that the strongest correlation is with geometric factors. The hydraulic factors exhibited very poor correlation.

g. Laboratory flume studies conducted to date reveal that the maximum rate of headward knickpoint erosion occurs when there is a maximum undermining of the less resistant underlying material, that venting of the waterfall is an important factor in controlling the rate of erosion, and that maximum erosion does not necessarily occur at maximum discharge.

h. Results of the laboratory flume studies combined with hypothetical flood hydrographs indicate that two erosional windows or thresholds (which limit maximum scour activity and headcutting) exist as a function of stratigraphy and its influence on knickpoint height. Second phase erosional activity (on the falling limb of the flood hydrograph) appears to be more pronounced (than on the rising limb) because of additional time involved in the fall of the discharge.

Recommendations

77. On the basis of the research studies described in this report and the conclusions derived from these studies, the following recommendations are offered:

a. Conduct detailed characterization and mapping with special attention to rock mass and lithostratigraphic discontinuities in the emergency spillway channels at reservoirs having experienced spillway flow and those at which future flow events may be expected.

b. Document thoroughly, including aerial imagery and topographic mapping the effects of a spillway flow to ensure that these effects may be included in the REMR data base and, thereby, compared with the erosion effects at other sites. Also, include the possible effects of spillway erosion in periodic performance inspections.

c. Initiate hydraulic model studies at sensitive projects whereby spillway geometries are evaluated in terms of geology and nature and spacing of discontinuities.

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Table 1

Hydraulic Parameters Reflecting Emergency Spillway

Flow Conditions for CE-SCS Data Base

Site		1 Q Peak cfs	2 Oe acre-ft	3 Oe/b acre-ft/ft	4 Flow Duration hr	5 Maximum Reservoir Stage ft	6 Maximum Flow Depth ft	7 Maximum Velocity fps	8 Froude Number
Kentucky	UTR No. 3	1,690	864	10.8	27	4	2.2	9.1	1.08
Kentucky	UTR No. 8	730	240	6	17	3.7	2.01	8.3	0.73
Kentucky	UTR No. 10	800	550	27.5	38	5	3.23	11.5	1.13
Kentucky	WFPR No. 5	2,360	1,180	11.8	25	3.8	2.35	17.3	2.0
Kentucky	WFPR No. 11	820	470	23.5	39	4.9	3.28	9.7	0.94
Kentucky	EFPR No. 7B	350	334	16.7	49	6.2	1.97	8.2	1.02
Kentucky	EFPR No. 9	850	488	12.2	33	3.5	2.21	10.2	1.21
Kentucky	EFPR No. 9A	510	250	12.5	28	3.9	2.46	11.9	1.34
Kentucky	EFPR No. 9B	540	206	10.3	19	3.8	2.55	8.6	0.95
Arkansas	WFPR No. 10	3,470	1,855	10.6	25	3.7	2.12	10.8	1.31
Arkansas	EFPR No. 1	2,240	2,067	15.9	28	3.5	1.95	9.1	1.15
Arkansas	EFPR No. 2	7,130	5,730	19.1	29	4.3	2.36	11.8	1.35
Arkansas	EFPR No. 4	3,200	3,140	15.7	40	3.4	1.86	9.9	1.28
Arkansas	EFPR No. 9	2,430	2,010	20.1	35	4.3	2.4	11.5	1.31
Texas	Grapevine	9,100	148,000	296	512	4	2.01	9.5	0.99
Iowa	Saylorville	17,200	203,390	473	372	5	3.23	8	0.78

Note:

1. Q peak = highest volumetric flow rate during flow event (cubic feet/second or cfs).
2. Oe = cumulative amount of water that flowed over spillway crest (acre-ft).
3. Oe/b = hydraulic attack, cumulative flow divided by spillway width (acre-ft/ft).
4. Flow duration = time it took for spillway flow event to pass (hours).
5. Maximum reservoir stage above spillway crest.
6. Maximum flow depth in excavated spillway channel (assuming supercritical flow).
7. Maximum velocity = highest flow velocity in the excavated spillway channel (fps).
8. Froude Numbers (dimensionless) calculated for upstream excavated section only.

Table 2

Geometric Parameters at Emergency Spillway

Channels in CE-SCS Data Base

Site		1 Channel Width ft	2 Excavated Length ft	3 Steep Length ft	4 Gradient (excavated)	5 Gradient (steep)	6 Elevation Drop ft
Kentucky	UTR No. 3	80	485	--	0.024	0.05	17
Kentucky	UTR No. 8	40	185	--	0.025	0.2	24
Kentucky	UTR No. 10	20	198	100	0.04	0.1	12
Kentucky	WFPR No. 5	100	140	160	0.04	0.16	1
Kentucky	WFPR No. 11	20	100	--	0.02	0.1	20
Kentucky	EFPR No. 7B	20	200	--	0.0276	0.2	24
Kentucky	EFPR No. 9	40	225	180	0.04	0.2	19
Kentucky	EFPR No. 9A	20	230	--	0.025	0.15	29
Kentucky	EFPR No. 9B	20	85	--	0.0235	0.3	26
Arkansas	WFPR No. 10	175	[illegible]	200	0.022	0.07	20
Arkansas	EFPR No. 1	130	290	200	0.021	0.17	30
Arkansas	EFPR No. 2	300	440	--	0.022	0.03	20
Arkansas	EFPR No. 4	200	700	300	0.025	0.04	35
Arkansas	EFPR No. 9	100	250	100	0.019	0.32	30
Texas	Grapevine	500	800	600	0.01	0.072	40
Iowa	Saylorville	430	1,300	2,500	0.01	0.025	63

Note:

1. Channel bottom width = width of excavated channel section, also same width as weir (ft).
2. Excavated length = length of excavated channel section (ft).
3. Steep length = length of steep channel section at the downstream end of the excavated section (ft).
4. Gradient (excavated) = channel gradient in the excavated section (no units).
5. Gradient (steep) = channel gradient in the steep section (no units).
6. Elevation drop = drop in elevation from the end of the excavated section to the floodplain (ft).

Table 3

Erosional Damage Parameters for Emergency

Spillway Flow in CE-SCS Data Base

Site		1 Total Volume Eroded cu-yd	2 Excavated Volume Eroded cu-yd	3 Unit Volume Eroded cu-yd/ft	4 Failure Volume cu-yd	5 Horizontal Gully Recession ft
Kentucky	UTR No. 3	14,000	1,000	12.50	10,993	400
Kentucky	UTR No. 8	2,000	100	2.50	6,578	10
Kentucky	UTR No. 10	1,500	100	5.00	1,760	50
Kentucky	WFPR No. 5	2,000	700	7.00	3,111	60
Kentucky	WFPR No. 11	2,000	0	0.00	1,481	0
Kentucky	EFPR No. 7B	2,500	100	5.00	3,556	125
Kentucky	EFPR No. 9	3,000	600	15.00	7,600	20
Kentucky	EFPR No. 9A	2,000	100	5.00	3,407	45
Kentucky	EFPR No. 9B	500	0	0.00	1,259	0
Arkansas	WFPR No. 10	0	0	0.00	8,267	25
Arkansas	EFPR No. 1	6,376	2,122	16.32	8,632	120
Arkansas	EFPR No. 2	0	0	0.00	11,733	0
Arkansas	EFPR No. 4	3,320	3,320	16.60	9,578	300
Arkansas	EFPR No. 9	4,284	4,284	42.84	14,591	25
Texas	Grapevine	209,385	46,174	92.3	146,320	300
Iowa	Saylorville	277,000	13,065	30.36	36,111	450

Note:

1. Total volume eroded from spillway channel (cu yd).
2. Volume eroded from excavated portion of spillway channel (cu-yd).
3. Unit volume eroded = total volume eroded/channel width (cu yd/ft).
4. Failure volume = postulated volume that would be eroded if gully did extend the length of the excavated section (cu-yd). This volume was calculated using the following formula:

   (Equilibrium Gully Mouth Area × 80 percent of channel length) + {[(Equilibrium Gully Mouth Area + 0)/2] × 20 percent of channel length}

   where the equilibrium gully mouth area is the actual gully mouth area measured in the field or taken from Figure 14, whichever area is larger.
5. Horizontal Gully Recession = distance headcut of gully eroded upstream in the excavated section of spillway channel (ft).

Table 4

Volumetric and Horizontal Erosion Rankings (percent)

For Dams in CE-SCS Data Base

Site		1 Volumetric Erosion Ranking, percent	2 Horizontal Erosion Ranking, percent
Kentucky	UTR No. 3	9	82
Kentucky	UTR No. 8	2	5
Kentucky	UTR No. 10	6	25
Kentucky	WFPR No. 5	23	43
Kentucky	WFPR No. 11	0	0
Kentucky	EFPR No. 7B	3	63
Kentucky	EFPR No. 9	8	9
Kentucky	EFPR No. 9A	3	2
Kentucky	EFPR No. 9B	0	0
Arkansas	WFPR No. 10	0	8
Arkansas	EFPR No. 1	25	41
Arkansas	EFPR No. 2	0	0
Arkansas	EFPR No. 4	35	42
Arkansas	EFPR No. 9	7	10
Texas	Grapevine	32	38
Iowa	Saylorville	36	35

Note:

1. Excavated volume eroded/failure volume × 100.
2. Horizontal gully recession/length of excavated section × 100.

Table 5

Correlation (R-Squared) Values for Comparisons of Volumetric and Horizontal Rankings with Hydraulic and Geometric Parameters (SCS Dams Only)

Erosion Ranking Parameter	R-Squared Values Linear	Polynomial
Volumetric		
Hydraulic parameters		
Peak flow	0.02 (P)	0.11 (MI)
Cumulative flow	0.06 (P)	0.18 (MI)
Hydraulic attack	0.00	0.00
Flow duration	0.02 (P)	0.03 (P)
Maximum stage	0.17 (N)	0.18 (N)
Maximum velocity	0.06 (P)	0.14 (MA)
Geometric parameters		
Excavated channel width	0.09 (P)	0.23 (MI)
Excavated channel length	0.45 (P)	0.50 (P)
Steep section length	0.44 (P)	0.79 (MI)
Excavated gradient	0.04 (N)	0.23 (MA)
Steep section gradient	0.03 (N)	0.14 (MA)
Elevation drop	0.01 (P)	0.23 (MI)
Horizontal		
Hydraulic parameters		
Peak flow	0.02 (N)	0.03 (MI)
Cumulative flow	0.01 (N)	0.01 (N)
Hydraulic attack	0.00	0.05 (MA)
Flow duration	0.10 (P)	0.14 (MA)
Maximum stage	0.04 (P)	0.06 (P)
Maximum velocity	0.00	0.18 (MA)
Geometric Parameters		
Excavated channel width	0.00	0.01 (N)
Excavated channel length	0.22 (P)	0.23 (P)
Steep section length	0.18 (P)	0.45 (MI)
Excavated gradient	0.02 (P)	0.17 (P)
Steep section gradient	0.06 (N)	0.07 (N)
Elevation drop	0.03 (N)	0.02 (N)

Note: P = positive slope, N = negative slope, MA = maxima, MI = minima (maxima refers to a convex upward curve and minima refers to a concave upward curve).

Table 6

Correlation (R-Squared) Values for Comparisons of Volumetric and Horizontal Rankings with Hydraulic and Geometric Parameters (Combined, CE-SCS Dams)

Erosion Ranking Parameter	R-Squared Values Linear	Polynomial
Volumetric		
Hydraulic parameters		
Peak flow	0.37 (P)	0.56 (MI)
Cumulative flow	0.42 (P)	0.55 (MI)
Hydraulic attack	0.41 (P)	0.55 (MI)
Flow duration	0.40 (P)	0.48 (MI)
Flow depth	0.03 (N)	0.06 (MI)
Maximum velocity	0.15 (P)	0.16 (MA)
Geometric parameters		
Excavated channel width	0.44 (P)	0.58 (MI)
Excavated channel length	0.62 (P)	0.74 (MI)
Steep section length	0.31 (P)	0.50 (MI)
Excavated gradient	0.09 (N)	0.38 (MA)
Steep section gradient	0.14 (N)	0.27 (MA)
Elevation drop	0.30 (P)	0.59 (MI)
Horizontal		
Hydraulic parameters		
Peak flow	0.01 (P)	0.15 (MA)
Cumulative flow	0.02 (P)	0.18 (MA)
Hydraulic attack	0.02 (P)	0.17 (MA)
Flow duration	0.03 (P)	0.18 (MA)
Flow depth	0.04 (P)	0.05 (P)
Maximum velocity	0.01 (P)	0.12 (MA)
Geometric parameters		
Excavated channel width	0.01 (P)	0.13 (MA)
Excavated channel length	0.12 (P)	0.25 (MA)
Steep section length	0.06 (P)	0.22 (MA)
Excavated gradient	0.00	0.00
Steep section gradient	0.08 (N)	0.08 (N)
Elevation drop	0.00	0.12 (MA)

Note: P = positive, N = negative, MA = maxima, MI = minima (maxima refers to convex upward curve and minima refers to a concave upward curve).

Table 7

Qualitative Summary of Knickpoint Erosion in Terms of Venting, Z/Y Ratio, and Position on Hydrograph

Venting	Ratio, Z/Y	Position on Hydrograph: Rising Limb	Falling Limb
Yes	>8/1	Erosion	Erosion
Yes	<8/1	No	No
No	Ratio not critical	Erosion	Erosion

Note: The unvented situation produces the most severe erosion.

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